FUNCTIONAL HUMAN ARM MOTION STUDY
WITH A NEW 3-D MEASUREMENT SYSTEM
(VCR-PIPEZ-PC)

by

Reza Safaee-Rad

A Thesis

Submitted to the Faculty of Graduate Studies

in Partial Fulfillment of the Requirements for the Degree of

Master of Science

The University of Manitoba

Department of Electrical Engineering

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ABSTRACT

The problem of the design of a prosthetic arm controller and one approach to this problem based on a fundamental study of functional human arm motion is discussed. To provide a proper basis and direction for this fundamental study, a classification of natural human arm movements is formulated. To study different aspects of the approach, a new 3-D measurement system was developed. The dynamic error of the system is between - .85% to 2.65%. The arm motions of ten subjects performing three feeding tasks were videotaped and subsequently processed by a PC based image acquisition system. Euler angles are used to simultaneously determine the required range and arc of eight arm joint rotations at the shoulder, elbow, and wrist for three feeding tasks. The movement pattern is shown by three stick diagrams in three orthogonal planes. Also angle-time graphs of eight joint rotations are presented. It is concluded that elbow flexion and forearm supination-pronation are the most important elementary motions and versatile fixed positions of 15° of wrist extension and 10° of ulnar deviation are recommended.

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CHAPTER 1

INTRODUCTION

1.1 PREFACE

Four decades of research and development in the field of EMG-Controlled prosthetic arm has established that the problem of control is the most important, difficult, and challenging problem in this field. This was observed in 1967 by Mckenzie [Mckenzie, 1967, 1] and the last two decades have proven the validity of this observation.

The reason for this is readily understood when the number of degrees of freedom (DOF) of the natural arm is considered. The basic components of the natural arm are bone, muscle, and joint (number: 32, 60, and 28 respectively) and if these components are considered together, the number of DOF of the natural arm can be estimated. According to one estimate, each arm has approximately 87 gross external mechanical degrees of freedom [Jacobsen, et al. 1982, 2]. It is clear that developing a control system that simultaneously and sequentially controls this number of DOF by EMG signals is, if not impossible, at least extremely difficult. The difficulty and complexity of this problem can be clearly seen by considering the available commercial EMG-Controlled prosthetic arm: after fourty years the only functional, practical, and cosmetic prosthetic arm of this kind has just one DOF.

The first objective of this study is to formulate an approach to the design of a prosthetic arm controller. This has not been well defined or studied before. The second objective of this study is to implement this approach to the extent of establishing the fundamental basis for future studies, i.e. the fundamental questions that should be studied and answered, the required instrumentation (hardware and software). The third objective is functional arm motion study of a few selected activities of daily life. Based on the results of a thorough and detailed study of this kind, a functional and practical control strategy can be formulated and developed.

The approach is based on functional human arm motion study. So the first phase of this study was to formulate a well-defined classification of human arm motion. The second phase was to develop a new three dimensional measurement system for studying functional arm motion patterns. The final phase was to use the classification of arm motion and the three dimensional measurement system for the analysis of feeding, an important daily life activity.

1.2 PROBLEM STATEMENT

There can be two approaches to the design of a prosthetic arm controller. One approach is to develop a functional and practical control system that is capable of simultaneous control of more degrees of freedom. There have been many studies in Europe, the U.S.A., and Canada for this approach in the last forty years. Many sophisticated control strategies have been developed but as Jacobsen wrote [Jacobsen, et al. 1982, 2]:

> These methods [...] are not refined, and typically involve complex decision processes for their implementation. Furthermore, "simple" problems, such as convenience, reliability, number of recording channels required, time delays, and controller

> dynamics minimize the chance of their early application.

The other approach to the same problem is to minimize the number of degrees of freedom that is necessary for a prosthetic arm. The philosophy of this approach is based on the fundamental point that it is more practical, effective, and fruitful to concentrate on providing a limited number of degrees of freedom and thus limited number of useful arm movements than to provide a prosthetic arm capable of all degrees of freedom encountered in the natural arm (if of course developing such a prosthetic arm is possible at all).

In order to minimize the number of degrees of freedom which are controlled naturally by the brain through EMG signals, the first step is to narrow the range of tasks which are performed by the prosthetic arm to the most vital, crucial and useful ones. Based on this, the following aspects can be studied:

- coupling of single joint rotations or different joint rotations,
- elimination of some arm joint rotations based on the priority and importance of various joint rotations,
- sequential joint rotations and joint locking,
- determination of a versatile axis of rotation for a joint,
- pre-position settings,
- pre-programming specific tasks.

A few studies have addressed some of the above aspects in the design of a prosthetic or orthotic arm [Carlson, et al. 1977, 3; Reswick, 1970, 4; Funakubo, et al. 1980, 5], but not all of these aspects have been used in the design and further none of the arms are EMG-controlled.

In order to study the above-mentioned aspects, a fundamental study of the functional movement of a natural arm is required which is the research in this thesis. The short term R & D, objective of this study is to narrow the functional capabilities of the prosthetic arm to the most vital ones. In terms of long term R & D, the research objective is to minimize the number of degrees of freedom to be controlled by the brain through EMG signals for a universal prosthetic arm (i.e. capable of performing all tasks).

This kind of fundamental study, which provides the functional range of arm joint motion, also

- helps in the assessment of functional loss and the effectiveness of treatment of patients with different arm joint disease, and
- aids in the development of arm joint prosthesis, (i.e. elbow, and wrist joint prostheses).

1.3 LITERATURE REVIEW

There have been very few fundamental studies which considered the functional movements of the natural arm and most of these were concerned with only a few aspects of the overall problem. For example typical studies consider only just one joint. In this section, a brief review of the literature in the field is presented.

Keller, Taylor, and Zahm at UCLA [Keller, et al. 1947, 6; Taylor, 1951, 7; Taylor, 1954, 8; Taylor, 1955, 9] were the first group to study the functional requirements for an arm prosthesis. The aim of this study was to determine the essential movements for 51 activities of daily living (ADL). They used a photographic method and a kinematic analyzer to determine joint rotations. They could only measure the extreme angular positions and not the pattern of joint rotation. Only one subject who had been trained prior to the study was used. The published data did not cover two of the three shoulder rotations. Further, the data for the functional range of rotations were combined and only one range that covered all 51 ADL was given. Based on the frequency distribution of the different rotations, they determined the priority and importance of the various joint rotations. Other important points that were studied were joint locking, coupled rotations, pre-position settings, and compensation for eliminated rotations or limited joint rotations by other joint rotations or by the head and trunk. The system of measurement that was used is time consuming, not very accurate, and difficult to use. However this study is still, because of its originality, breadth of problems covered, and lack of similar studies, a valuable reference.

A later study by Enger at the Prosthetic Research Laboratory of the Norrbacka Institute - Stockholm [Enger, 1967, 10] investigated the possibility of eliminating two of the three shoulder joint rotations, i.e., a shoulder joint with only one degree of freedom. He described this versatile single-axial exo-skeletal prosthetic shoulder joint and showed that it had ample mobility for feeding.

Engen and Spencer at the Texas Institute for Rehabilitation and Research [Engen et al. 1968, 11; Engen et al. 1969, 12] indicated "a need for detailed analysis of the complex, synchronized musculoskeletal actions in normal upper extremity motions involved in daily activities". This study was begun in the early 1965 and ended in 1969. They used the photographic method and a manually operated x-y recorder. As a part of this study, nine subjects were used for the kinematic study of a normal arm while performing five basic functions. Based on collected data, stick diagrams for the three orthogonal planes were plotted manually. Although they recognized the importance of the functional study of arm movement and briefly discussed important points such as joint fixation and pre-setting of elbow joint for specific tasks, they did not determine the functional range of motions for different joint rotations. Also there are not any graphs in the reports that show the angular rotations of each arm joint with respect to time.

Davis at the University of Surry, Guildford [Davis, 1977, 13] also studied by simple observation the frequency and functional range of arm joint motion. The number of subjects in this study was nine. The problem with a study of this kind is its inaccuracy. Further the published data were only for group of activities not for any specific task.

Chao, An, Askew, and Morrey at the Mayo Clinic/Mayo Foundation [Chao et al. 1980, 14; Morrey et al. 1981, 15] studied functional elbow joint rotations. They used a triaxial electrogoniometer. In this study, 15 male and 18 female subjects participated who performed fifteen ADL. Only elbow joint rotations were measured (Flexion-Extension: F-E, Pronation-Supination: P-S, Abduction-Adduction: A-A). A graphic display of the elbow joint angle measurements was given (angular rotation with respect to time). They also studied the variation in the movement patterns among normal subjects and compensatory motion for patients with elbow functional limitation, as well as priority and importance of each of the three elbow rotations.

Langrana at Rutgers University [Langrana, 1981, 16; Langrana, 1978, 17] developed a biplanar videotaping 3-D measurement system for arm motion study. The 2-D coordinates of different points were manually digitized. Only one basic activity, i.e. diagonal reaching activity, was studied and analyzed. Two subjects participated in this experiment. Also, only shoulder and elbow joint motions (each with three rotations) were measured. Motion patterns were shown by a stick-diagram, and the change of each joint rotation is shown by an angle-time graph.

Brumfield, and Champaux at Rancho Los Amigos Hospital [Brumfield et al. 1984, 18] studied normal functional wrist motion. They used a uniaxial electrogoniometer to determine the range of wrist joint flexion-extension for 15 ADL. Nineteen normal adult subjects participated in this experiments. They suggested a versatile position for wrist fusion.

Palmer, Werner, Murphy, and Glisson at Upstate Medical Center, Syracuse, N.Y. [Palmer et al. 1985, 19] also studied functional wrist motion. They used a triaxial electrogoniometer to study three functional wrist joint rotations for 52 standardized tasks (26 ADL). Ten normal subjects participated in this study. A histogram was used to show the study's results for 26 ADL.

Compared to all of the above-mentioned studies, this study has the following features that distinguishes it from all others:

(1) The implication of functional arm motion study for developing a control strategy is formulated clearly.

(2) A clear base and direction for functional arm motion study is provided by the given arm motion classification.

(3) The 3-D measurement system that is developed for functional arm motion study is:

- a new system in that an image processing board (PIPEZ) is used instead of manual digitizer; thus by using computer programs the two dimensional coordinates can be calculated automatically,
- much easier to use in clinical environment,
- much faster compared to stereometric systems that were used in arm motion study,
- capable of providing the pattern of movement automatically (stick diagram).

(4) Simultaneously provides eight rotations for the three arm joints.

(5) Study had ten subjects. The only other comparable study [Keller et al. 1947, 2] was based on one subject.

As a result of these features, it will be much easier to study and answer all the problems that were formulated at the beginning of this chapter, and thus provide a better understanding of functional movement of the arm and its specific implications on developing new control strategies for a prosthetic arm.

Here, it should be noted that in this study only the positioning component of the arm is studied and thus the hand and specifically the fingers are not considered. In fact in the last few decades more studies have been done on finger movement patterns and classification of hand movements than on the positioning component of arm [2, 20-37].

The next four chapters discuss and explain the following aspects of the research study. In Chapter 2 a general background on arm movement is presented which covers the functional anatomy of a human arm and the classification of arm movements. The new 3-D measurement system that has been developed for functional arm motion study is explained in Chapter 3. Chapter 4 presents data which have been collected for seven functional joint rotations and also analyze these data. Finally Chapter 5 contains discussion, conclusions and recommendations.

The Appendices give a complete list of all the computer programs developed for the 3-D measurement system, hardware component technical specifications, and detailed collected data.

CHAPTER 2

CLASSIFICATION OF ARM MOVEMENTS

In this chapter, two topics are discussed. The first is a brief presentation of the functional anatomy of the human arm. The second is a formulation of a general classification of human arm motion based on the available but scattered information about this topic (e.g. ergonomics, medicine, engineering).

2.1 FUNCTIONAL ANATOMY OF HUMAN ARM

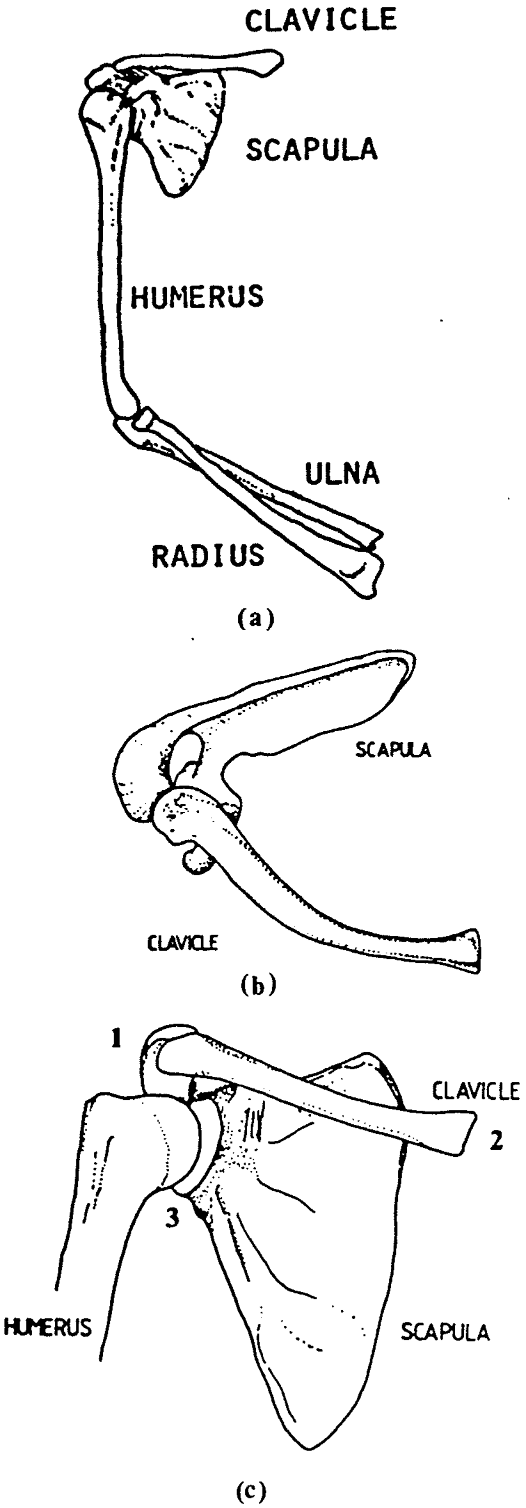
The basic anatomical components of the arm are (as shown in Figures 2.1, 2.2, 2.3): bone, muscle, and joint. The number of skeletal bones in the different parts of an arm are [Schade, 1974, 1]:

- shoulder girdle	2
- upper arm	1
- forearm	2
- hand	27

Approximately 60 paired muscle groups are directly or indirectly involved in the arm movement and are distributed as follow [Schade, 1974, 1; Vokubratovic et al. 1972, 2]:

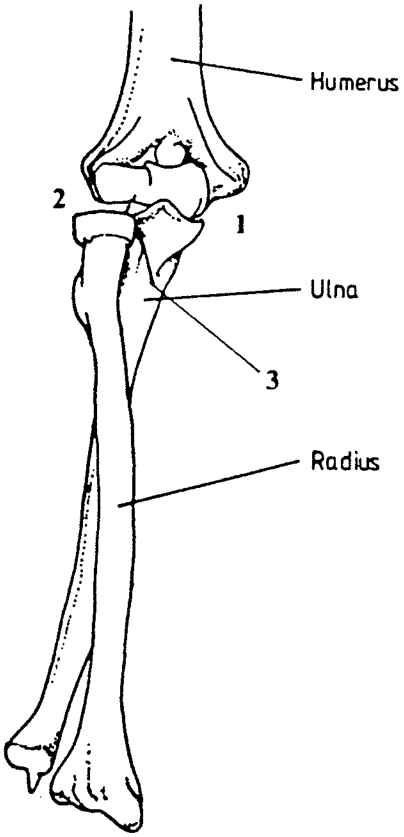
- upper extremities	26
- back	56
- chest	26

There are 28 joints in the human arm [Berme et al. 1985, 3]:



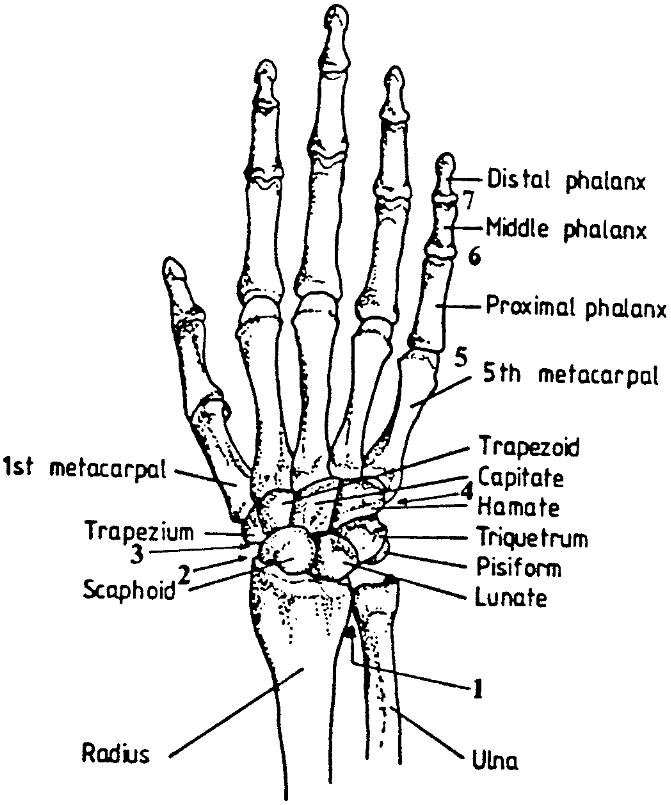
(1) Acromioclavicular joint
(2) Sternoclavicular joint
(3) Glenohumeral joint

Fig.2.1 a) Anatomy of the upper extremity system ,
b) right shoulder girdle from above , and
c) right shoulder girdle from anterior view.



(1) Humeroulna joint
(2) Humeroradial joint
(3) Superior radioulna joint
(4) Inferior radioulna joint

Fig.2.2 Anterior view of right arm bones (hand pronated).



(1) Inferior radioulna joint
(2) Radiocarpal joint
(formed by the scaphoid , lunate, and triquetrum distally and by the radius and radioulna disc proximally)
(3) Midcarpal joint
(formed by the two rows of carpals)
(4) Carpometacarpal joints [5]
(5) Metacarpophalageal joints [5]
(6) Proximal interphalageal joints [5]
(7) Distal interphalageal joints [4]

Fig.2.3 Dossal aspect of the bones of right hand and wrist.

- shoulder	3
- elbow	3
- wrist	
inferior radioulnar	1
radio carpal (compound joint)	1
mid carpal (compound joint)	1
- hand	19

Each major human joint has six degrees of freedom: three translations and three rotations [Kinzel, et al. 1972, 4; Kinzel et al. 1983, 5].

If a human arm with these three basic components (which are 32, 60, and 28 respectively) is considered as a whole, one can estimate its total number of degrees of freedom. According to one estimate there are "approximately 87 gross external mechanical degrees of freedom and many, many more internal degrees of freedom" [Jacobsen et al., 1982, 6]. Another report estimates that "Altogether, the natural arm and hand account for something like 42 degrees of freedom" [Zimmerman, 1982, 7]. This high degree of freedom for a natural arm makes it a redundant system and thus an extremely flexible positioning and manipulating system.

The natural arm can be considered as having two functional components: a terminal device (TD) for grasping and manipulating objects (hand) and a means of positioning the TD in space (upper arm and forearm). This study is concerned only with the positioning component of the arm. So in classification of arm movements, the hand (palm and fingers) is not considered.

2.2 CLASSIFICATION OF ARM MOVEMENTS

The main objectives in providing a general classification of the extensive and extremely varied arm movements are:

- to have a better understanding of this extremely flexible part of the human body in general,
- to provide a proper direction and base for a 3-D study of human arm motion patterns,
- to determine the most crucial and vital functions and motion patterns that should be provided by a prosthetic arm (both for developing control strategies and for the mechanical design of a functional and practical prosthetic arm).

Here, it is appropriate to say a few words about other human limbs, i.e., lower limbs, in this context. In general, there have been more studies on lower limb motion patterns, primarily because the human lower limbs, in their most important function, walking, follow a repetitive cycle. The human gait cycle can be divided into three phases of activity in which the first and third phases are divided into three periods of distinct activity [Thornton-Trump, 1979, 8]. Thus human locomotion consists of just a few repetitive activities, which make it very easy to study and analyze.

Compared to human locomotion, arm motion is much more complex, and thus it is much more difficult to classify these types of motions. What is presented here, is a summarization and formulation of all the available studies in various fields of science and engineering that address different motion classification for different parts of the human arm and present it as a general human arm motion classification.

At first sight it would seem that the human arm movements are so extensive and varied that its classification would not be feasible. But various studies in the last few decades have shown that it is possible to classify arm motions into three groups:

1 - elementary motions,

2 - basic motions, and

3 - purposive motions.

What follows is a brief discussion of these three groups of arm motions.

2.2.1 ELEMENTARY MOTIONS

Elementary motions are all those motions that any complex motion can be decomposed to. The best known source for defining these elementary motions is the handbook of the American Academy of Orthopaedic Surgeons [AAOS, 1965, 9]. Terminology and neutral position for each motion are as follow (see Figures 2.4 to.2.8).

Shoulder:

- Abduction - Adduction
- Flexion - Extension
  - Forward - Backward
  - Horizontal
- Inward Rotation - Outward Rotation
  - With arm at side
  - In abduction

Elbow:

- Flexion - Extension (Hyperextension)

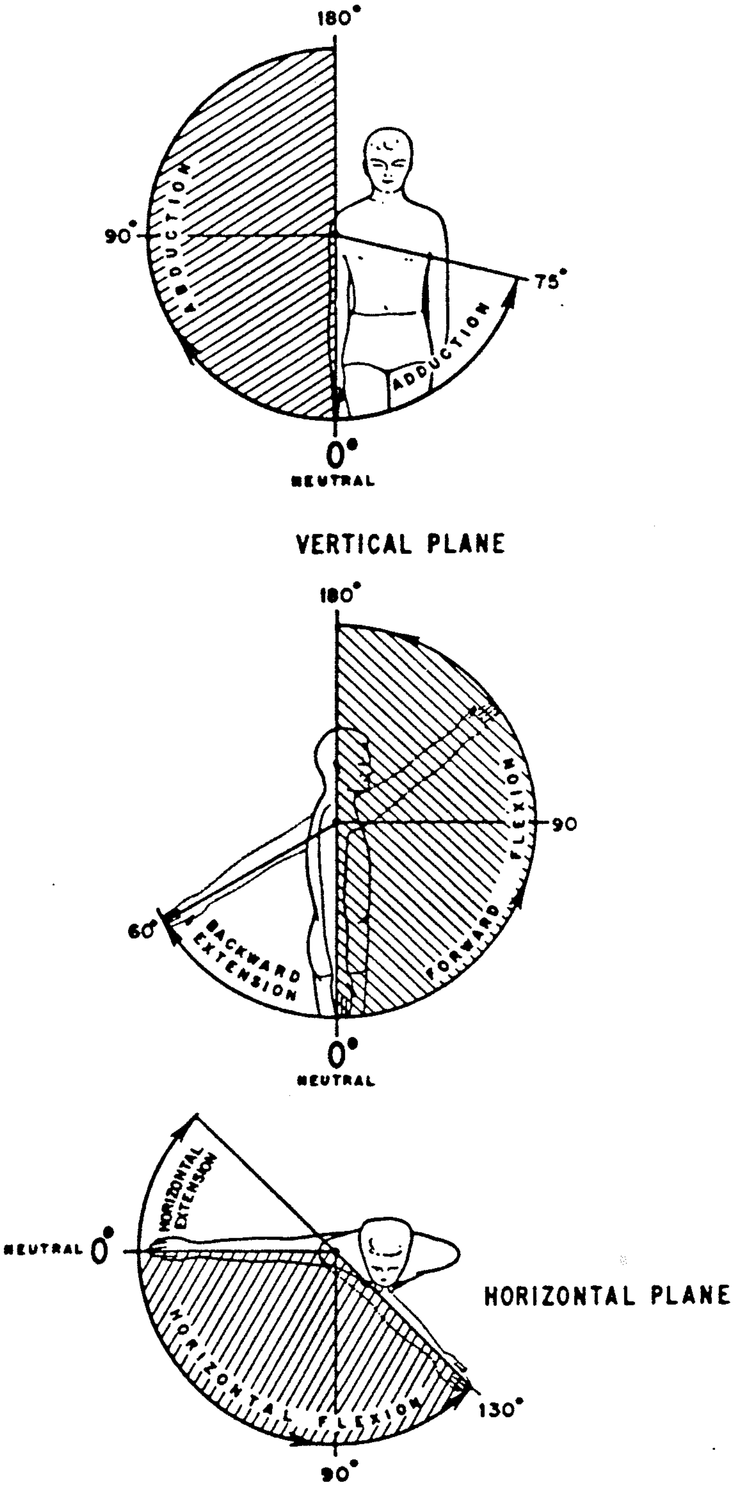
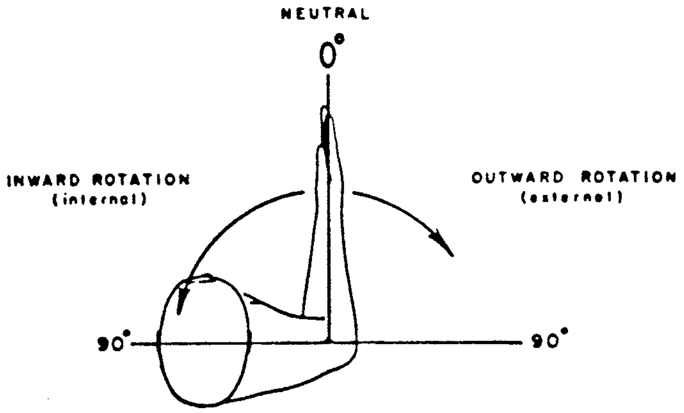
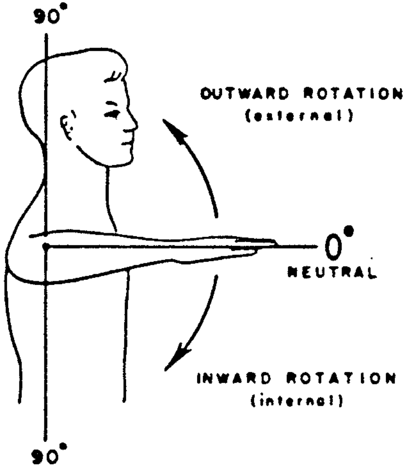


Fig.2.4 Motion of the arm at the shoulder (a).



ROTATION WITH ARM AT SIDE



ROTATION IN ABDUCTION

Fig.2.5 Motion of the arm at the shoulder (b).

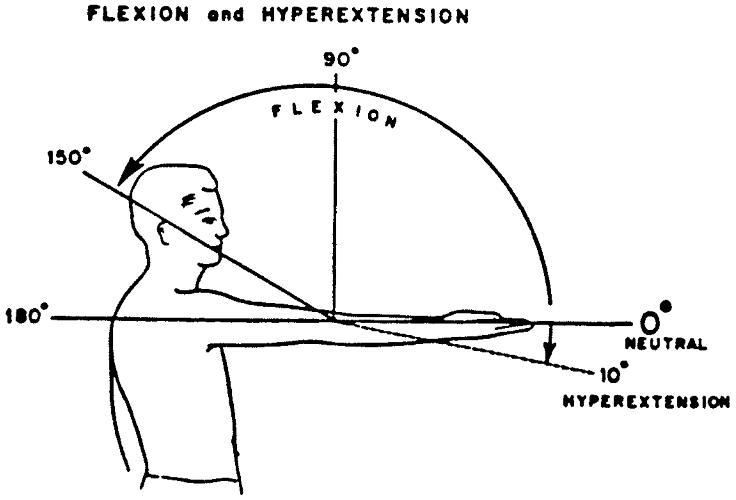
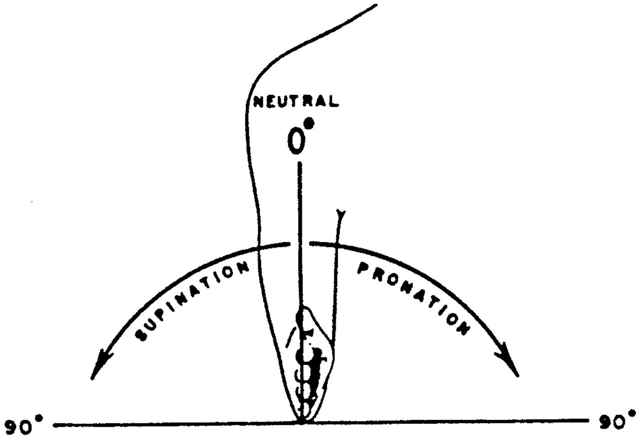
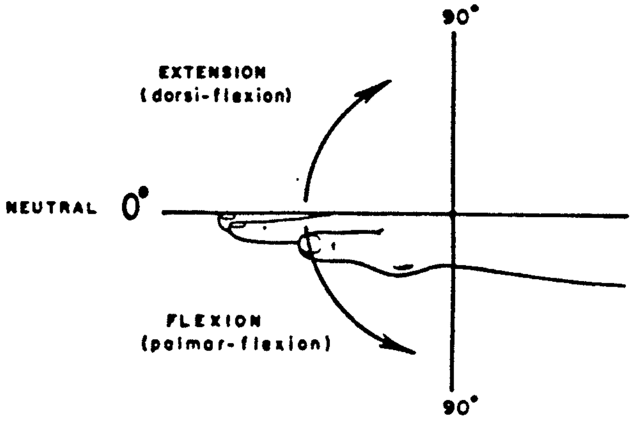


Fig.2.6 Motion of the arm at the elbow.

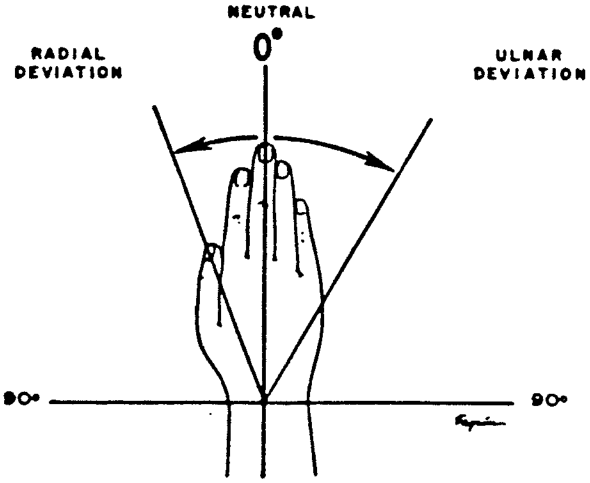


PRONATION and SUPINATION

Fig.2.7 Motion of the arm at the forearm.



FLEXION and EXTENSION



RADIAL and ULNAR DEVIATION

Fig.2.8 Motion of the arm at the wrist.

Forearm:

- Pronation - Supination

Wrist:

- Flexion - Extension
- Ulnar Deviation - Radial Deviation

It should be noted that in the above-mentioned figures the standard position and neutral position for each of the elementary motions are specified.

The range of these elementary motions as defined above are given in the AAOS handbook. But a more accurate study was done recently by Boone and Azen at the University of Southern California [Boone et al. 1979, 10]. In this study 109 normal male subjects, ranging in age from eighteen months to fifty-four years, participated. The results of this study for arm joints are shown in Table 2.1.

2.2.2 BASIC MOTIONS

Hancock [Hancock, 1977, 11] studied many manual industrial tasks and concluded that five basic motions comprise 97.5% of all motions used. These basic motions are [Karger et al. 1966, 12]:

1. Reach : "The basic hand and finger motion employed when the predominant purpose is to move the hand or fingers to a destination."
2. Grasp : "The basic finger or hand element employed to secure control of an object."
3. Move : "The basic hand or finger motion employed when the predominant purpose is to transport an object to a destination."

TABLE 2.1 Normal range of motion of human arm joints (Degrees)

Shoulder		
Horizontal Flexion		140.7±5.9
Horizontal Extension		45.4±6.2
Neutral Abduction		182.0±7.0
Forward Flexion		166.7±4.7
Backward Extension		62.3±9.5
Inward Rotation	In Abduction	68.8±4.6
Outward Rotation		103.7±8.5
Inward Rotation	At Side	68*
Outward Rotation		68*
Adduction		50*
Elbow		
Flexion		142.9±5.6
Extension		.6±3.1
Forearm		
Pronation		75.8±5.1
Supination		82.1±3.8
Wrist		
Flexion		76.4±6.3
Extension		74.9±6.4
Radial Deviation		21.5±4.0
Ulna Deviation		36.0±3.8

*This study did not provide data for these three rotations. These data are from AAOS handbook.

4. Position: The basic finger or hand element employed to align, orient, and engage one object with another to attain a specific relationship."

5. Release : "The basic finger or hand motion employed to relinguish control of an object, freeing the hand and finger for use in other motion."

Based on the above definitions and classification, basic motion has the following features:

- it is composed of elementary motions,
- it does not provide alone any purposive motion,
- combination of basic motions provides purposive motion.

This study considered only manual industrial tasks and these basic motions are defined for those types of tasks. However, a minor modification in the definition of these basic motions allows them to be applied to many activities of daily living (ADL). For example, for feeding tasks, the first four basic motions are applicable while the fifth (i.e., release) should be modified in such a way that covers unloading of food into the mouth (examples of feeding activity: eating with a spoon, eating with a fork, drinking a glass of water, ...).

Besides the decomposition of purposive motions into basic motions, this classification has another feature. It demonstrates the very important aspect of human arm movement which is the sequential nature of motions of the positioning (upper arm and forearm) and manipulating (hand) components of an arm in any task. It is easy to see that reach, move, and position basically are positioning component motions and grasp and release are manipulating component motions. Generally, in the majority of ADL, whenever one component is active, the other is locked. For example in bringing a glass of water to the mouth, during the move and position motions the hand and specifically the fingers do not move relative to each other, i.e., the fingers are locked. This sequential nature of the basic motions can be used very effectively in the development of control strategies for the prosthetic arm.

Another very important aspect of this classification is its use for the evaluation of a prosthetic arm and hand. Based on that recommendations for improvement can be made. An example is the study regarding artificial hands done by Gilad at Israel Institute of Technology [Gilad, 1982, 13; Ibid, 1985, 14; Ibid, 1986, 15].

2.2.3 PURPOSIVE MOTIONS

Purposive motion is a motion that is

- composed of elementary motions,
- can also be composed of basic motions,
- in itself is a complete activity, i.e., a task is performed; an example is drinking a glass of water.

Based on this definition, it is easy to see that feeding, for example, is a collection of different purposive motions such as:

- cutting with a knife
- eating with a fork
- eating with a spoon
- drinking from a glass
- pouring from a pitcher, etc.

The upper limbs utilize the three classes of motions discussed to perform all human activities, which can be divided into three groups:

- Activities of Daily Living (ADL),
- Working Activities (WA), and
- Leisure Activities (LA).

McWilliam at West Hendon Hospital - London [McWilliam, 1970, 16] compiled a list of tasks which covers all the activities of normal adult daily life (excluding jobs or recreations). This list is composed of 625 ADL.

2.3 PRIORITY AND IMPORTANCE OF MOTIONS

Determination of the priority and importance of different motions in each class is of high importance. The reasons are, firstly, it helps to narrow the number of motions to be studied for functional arm motion analysis; secondly, it helps to design and develop a more functional and practical prosthetic arm. It is clear that a study of functional human arm motions is partly concerned with the determination of priority and importance of these motions.

All functional arm motion studies agree that the feeding task is the most important task of all human activities for an amputee. This observation is based on clinical experience in different hospitals. McWilliam [McWilliam, 1970, 16] asked 17 normal adults (10 men and 7 women) to assess 625 different ADL. Three categories were used in order to score the priority and importance of 625 ADL: essential, useful, trivial. The following eating activities had a range of scores from 91 - 100%. Activities that were unanimously classed as essential are indicated by *:

- Load spoon from:
  - bowl
  - plate*
- Unload into:
  - plate

  mouth*
Use fork for impaling
Use fork as spoon
Use knife for:
  cutting
  pushing
  spreading
Stir with spoon*
Lift and tilt:
  cup*
  wine glass
  tumbler*
  jug
  bottle

Although it is not possible to omit any of the five basic motions, it is possible to determine the importance and priority of these motions for the natural and prosthetic arm. As was mentioned, Gilad studied this problem and, based on the methods time measurement (MTM) technique (a standardized procedure for analyzing manual operations in terms of their motion elements), he concluded that for a prosthetic hand, the basic motion grasp has the highest priority. Based on this conclusion, he recommended a few improvements in the design of the body-powered hook device.

Keller at UCLA [Keller et al. 1947, 17] studied the importance and priority of elementary movements in greater detail than any other study. Mason [Mason, 1972, 18] tabulated the result of the above-mentioned study (using elbow flexion as the standard unit of measure ≡1.00) as shown in Table 2.2.

Based on this study, Keller et al. concluded that wrist abduction-adduction can be eliminated entirely without important functional loss. Also from the above table which was based on 51 ADL,

TABLE 2.2. Relative importance of elementary motions.

Upper Arm	Relative Frequency	
Forward Flexion	.667	*
Extension	.248	
Abduction	.563	*
Internal Rotation	.720	*
External Rotation	.061	
Fore Arm		
Flexion	1.000	*
Pronation	.575	*
Supination	.200	
Wrist		
Flexion	.575	*
Extension	.194	
Adduction	.302	
Abduction	.097	

it is clear that elbow flexion, shoulder inward rotation, shoulder forward flexion, forearm pronation, wrist flexion, shoulder abduction have respectively the highest importance and priority among elementary motions (indicated by *).

This chapter has discussed briefly the functional anatomy of human arm, the importance of arm motion classification, a general classification of arm motion, and finally the priority and importance of the classified motions in each class. These aspects provide a clear base and direction for functional arm motion study. But before this, a proper 3-D measurement system should be developed. The following chapter discusses the hardware and software components of the new 3-D measurement system.

CHAPTER 3

3-D MEASUREMENT SYSTEM

Different 3-D measurement systems have been developed in the last few decades [Cappozo, 1985, 1; Winter, 1984, 2; Chao, 1978, 3; Atha, 1984, 4]. Although the precise instruments and techniques used in these methods are different, they generally follow similar principles in converting the measured raw data to the required joint kinematic information. One way of classifying these methods is as follows:

1. Stereometry
    - (a) Stereo photogrammetry
    - (b) Light-scanning system
    - (c) Stereosonic system
2. Exoskeletal Linkages
3. Accelerometry

Stereophogrammetry is basically a method to reconstruct of 3-D coordinates of a point in object space from at least two 2-D coordinates of the point in image spaces. This can be done using different instruments. Different systems that are based on this method are classified as follows:

1. Photography
    - (a) Still cameras
    - (b) Cine cameras
    - (c) TV cameras
2. Opto-electronic
3. X-ray
4. Tomography

All of the above stereometric systems have been used to study the kinematics of different human arm joints or human arm motion patterns.

Typical studies are: still cameras [Ayoub et al. 1970, 5; Fioretti et al. 1985, 6], cine cameras [Keller et al. 1947, 7; Engen et al. 1969,8; Nicol et al. 1977, 9; Erdman et al. 1979, 10], TV cameras [Langrana, 1981, 11], opto-electronic [Suzuki, 1981, 12], x-ray [Chao et al. 1978, 13], and tomography [Robbin et al. 1986, 14]. Other methods that have been used to study upper limb kinematics are: stereosonic [Andrews et al. 1979, 15; Brumbaugh et al. 1982, 16; Engen et al. 1984, 17; Engen et al. 1984, 18], and exoskeletal linkages [Chao et al. 1980, 19; Sommer III et al. 1980, 20; Morrey et al. 1981, 21; Brumfield et al. 1984, 22; Palmer et al. 1985, 23]. These systems have been reviewed and compared with each other [Cappozo, 1985, 1; Winter, 1984, 2; Chao, 1978, 3; Ahta, 1984, 4].

The basic hardware components of a photography system are still, cine or TV cameras and a projector for enlargement. Therefore, the recorded image is manually digitized. Opto-electronic systems, on the other hand, permit a direct feeding of the point projection information to a digital computer. Established opto-electronic systems, which are available are: VICON (England), SELSPOT (Sweden), CoSTEL (Italy), and EMR Schlumberger (U.S.A.).

The 3-D measurement system that was developed for functional human arm motion study in this project is a new system. The position of this new system in the above stereometric systems is somewhere between photographic and optoelectronic (VICON which uses TV cameras)systems. The basic features of this new system compared to the two above-mentioned systems are:

compared to a photography system

- more accurate,
- faster with respect to processing the images,
- much easier to use;

compared to an opto-electronic system

- more flexible in that it provides a permanent visual record for teaching and reanalysis; this feature should be emphasized because the information inherent in the photographic record is an order of magnitude more extensive than can yet be provided by the most sophisticated computer analysis technique; furthermore it can be extremely valuable in slow and stopped motion (frame-by-frame, 1/5, 1/10, and normal speed - 30 frames/sec.) assessments;
- much easier to use,
- cheaper.

Overall, this 3-D measurement system is much more convenient and suitable for clinical use than any other available system.

This chapter discusses and explains the new 3-D measurement system. Section 1 discusses the hardware components of the system and its set-up. The general procedure and different steps that are involved in using the system is explained in Section 2. The details of different techniques and algorithms that are used in the software components of the system are discussed in Section 3. The program listing is given in the Appendix (A). Microsoft FORTRAN (version 3.20) was used to write the programs.

3.1 HARDWARE COMPONENTS OF THE SYSTEM

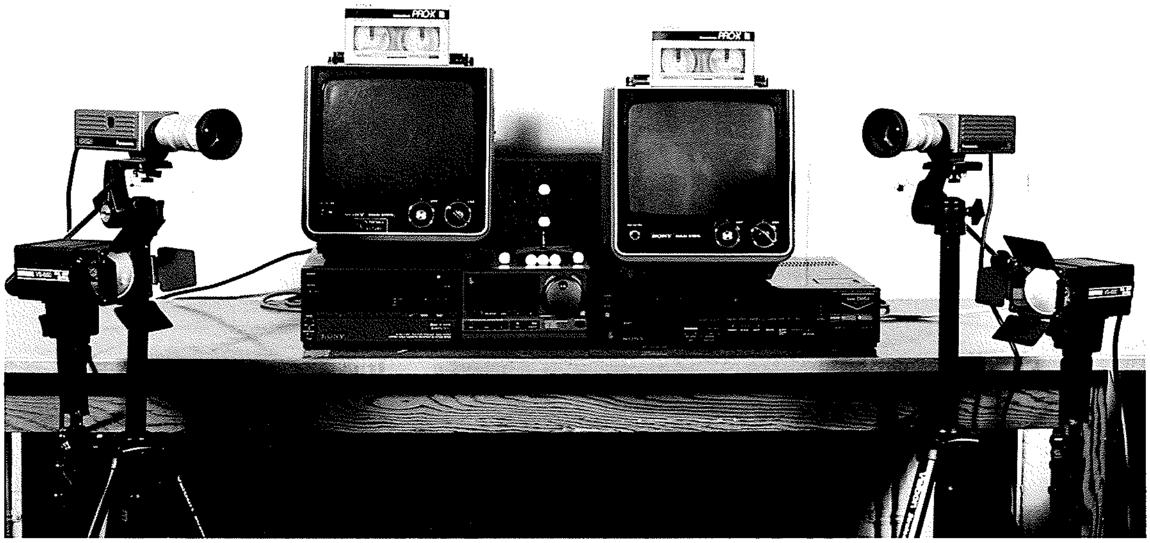
The system consists of the following equipment:

- two black-white video cameras,
- two zoom lenses,
- two video cassette recorders, one with frame-by-frame replay and frame counting capabilities,
- two video lights,
- two black-white monitors,
- a PC computer with PIPEZ image acquisition board,
- a monitor with computer and RGB (image) channels,
- a calibrating frame,
- seven spherical reflective markers.

Components of the system are shown in Figures 3.1, 3.2, and 3.3. The complete technical specifications of the equipment is given in Appendix (B).

The schematic figure of the system set-up as it is seen from the top is shown in Fig. 3.4. As seen, black curtains are used in order to make the background completely black. The angle between the two camera optical axes is choosen to be approximately 40 degrees. This makes all the markers on the arm visible at all times (preventing the problem of marker disappearance). Here it is noted that the larger this angle, the better is the measurement accuracy. However, a larger angle between the two camera optical axes causes an increase in data deficiency since it enlarges the unmeasureable areas of the image surface. The field of view of each camera can be adjusted by using the zoom lens.

Fig. 3.1 Image recording components of the system.

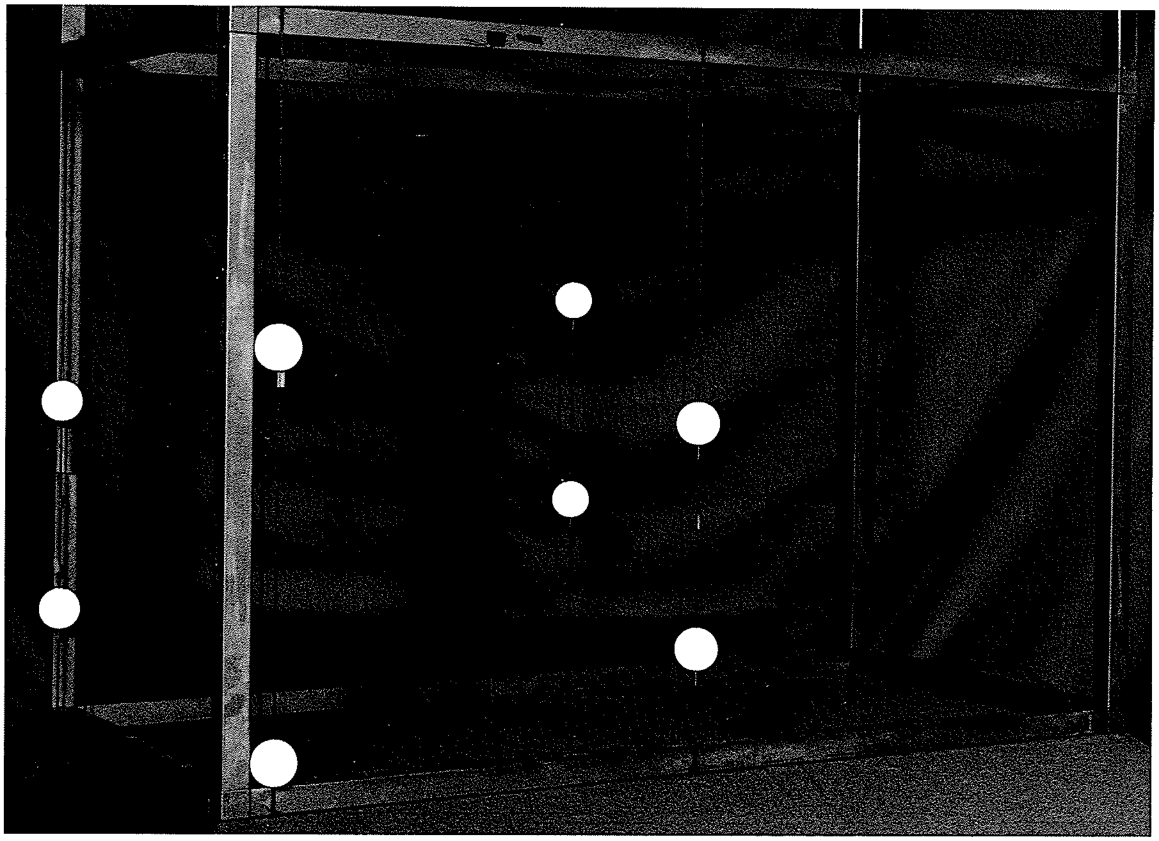


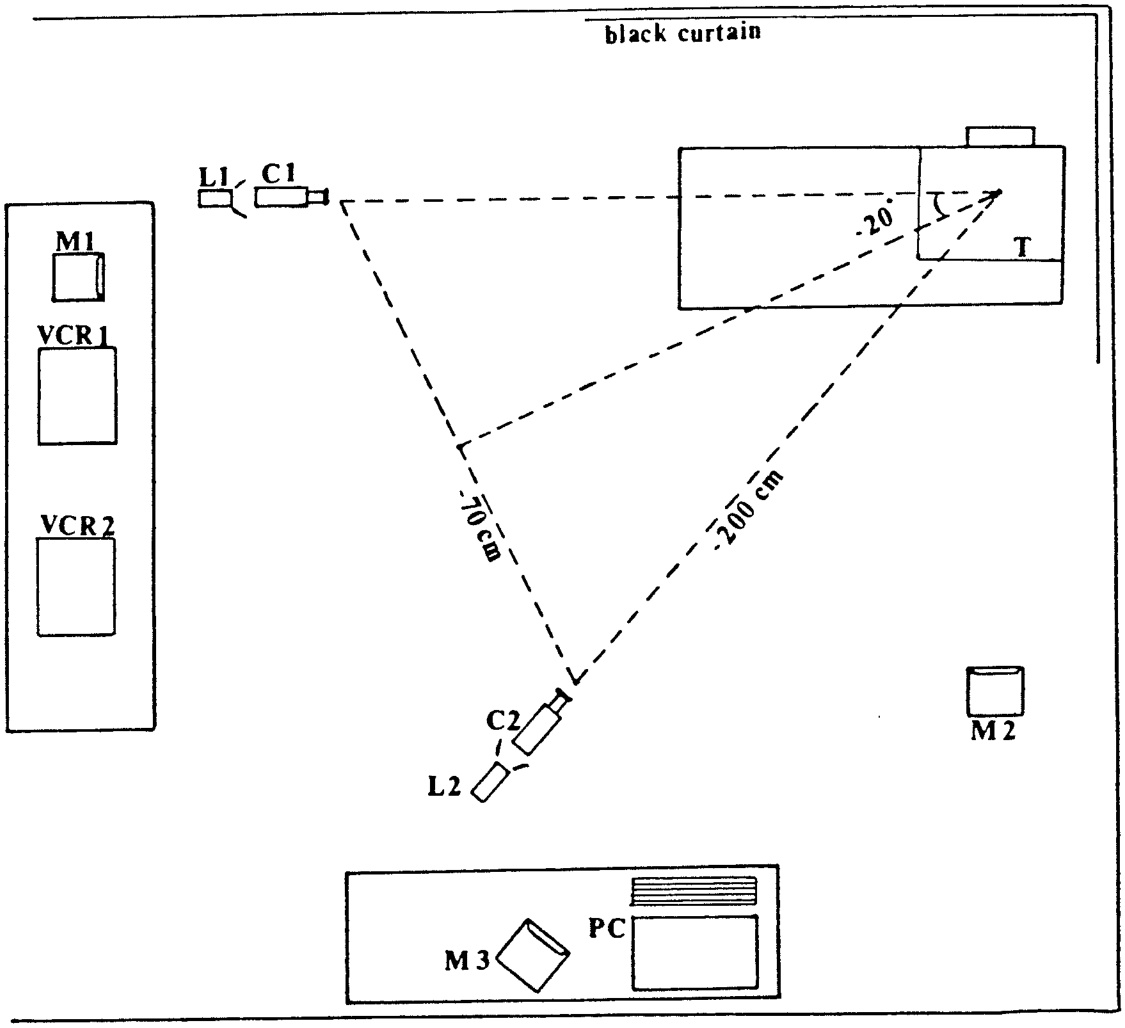
PRO X
PRO X
SONY

Fig. 3.2 Image processing system

32a

Fig. 3.3 Calibration frame





T : Area of table which is used to perform different tasks (table area of activity)

M1 & M2 : Black and white monitors

VCR1 & VCR2 : Video cassette recorders

C1 & C2 : Video cameras

L1 & L2 : Video lights

M3 : Image processing system monitor

PC : Personal computer with video digitiser board

Fig.3.4 Schematic diagram of system set-up.

The calibrating frame is shown in Fig. 3.3. In order to make it easy to use, the frame is movable. During calibration, the frame is put on the table in such a way that eight control markers are in the field of view of both cameras. After calibration, the frame is removed. The eight control markers are arranged in such a manner that the entire field of view of both cameras is covered and also that they are non-coplanar in order to prevent the singularity condition in the calculation of the eleven calibrating parameters.

3.2 3-D MEASUREMENT PROCEDURE

This section discusses 'how to use the system' step by step. Details of different techniques, algorithms and mathematical equations that are used in the programs are explained and discussed.

3.2.1. CALIBRATION OF THE SYSTEM

The position of the two cameras is fixed as shown in Fig. 3.4. The height of the activity table is 78 cm, while the height of the center of the zoom lens is approximately 90 cm. The cameras are leveled in both directions. It should be emphasised that the tripods for the cameras should be of good quality in order to maintain the cameras' positions and attitudes. Any small change in the position and attitude of either camera changes the calibration parameters completely and thus would cause large errors in the 3-D measurement. The 2.8 f-stop is used. The reasons are this setting requires a minimum amount of light, and, for limited arm movement space, it provides enough depth of field to have a focused image. The cameras are focused by using an object positioned at the center of the table area of activity (it is focused at ~ 200 cm). The required field of view is about 80 x 80 cm^2, and this is provided by a focal point of ~ 20 mm. Finally the lighting system should also be adjusted in such a way that the field of view of both cameras is properly illuminated, i.e., control markers, reference markers and the seven markers on the arm should be illuminated properly with a minimum amount of shadow and noise from other parts of the field of view. This is done by a trial and error method. It is possible to find an optimal position and attitude for lighting system in order to provide proper illumination. Once the optimal position and attitude (and also amount of illumination) are found, the lighting system can be fixed.

When all these camera-related parameters are fixed, the calibrating frame is put on the table, positioning the eight white control markers in the field of view of the two cameras. This can be checked by looking at the monitor of each camera. There should be a minimum of margin space between the control markers and the edges of the monitor screen (this is related to the image processing algorithm and is explained later in this chapter).

The 3-D coordinates of all eight control markers should be measured in meters to two decimal places. This degree of measurement accuracy is sufficient for the research of this thesis. The measurement is done with respect to the hypothetical fixed frame of reference (orthogonal) as shown in Fig. 3.5. The 3-D orthogonal axes are based on the Right

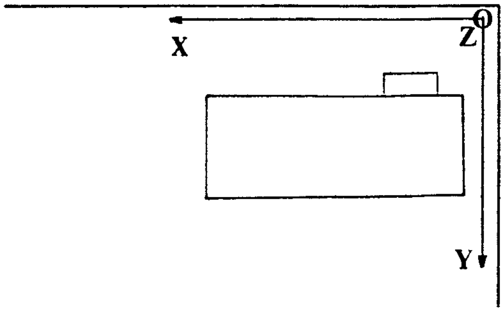


Fig. 3.5 Fixed frame of reference position.

Hand Rule (RHR). It should be emphasised that using the RHR and the above arrangement of x, y, and z axes are important for the calculation of Euler angles as explained later in the chapter. Once the 3-D coordinates of the eight control markers are measured, there is no need to repeat this measurement in later calibrations, as long as the calibration frame is placed in the same position (the relative positions of the eight markers with respect to the frame are fixed).

The static and fixed image of the control markers is captured by the PC-PIPEZ image processor. The grabbing, processing and finally calculation of 2-D coordinates of the control markers is done by using the program CALIB1.FOR for the first camera and CALIB2.FOR for the second camera. The 2-D coordinates of the control markers are stored in two files: TEM1.TXT and TEM2.TXT.

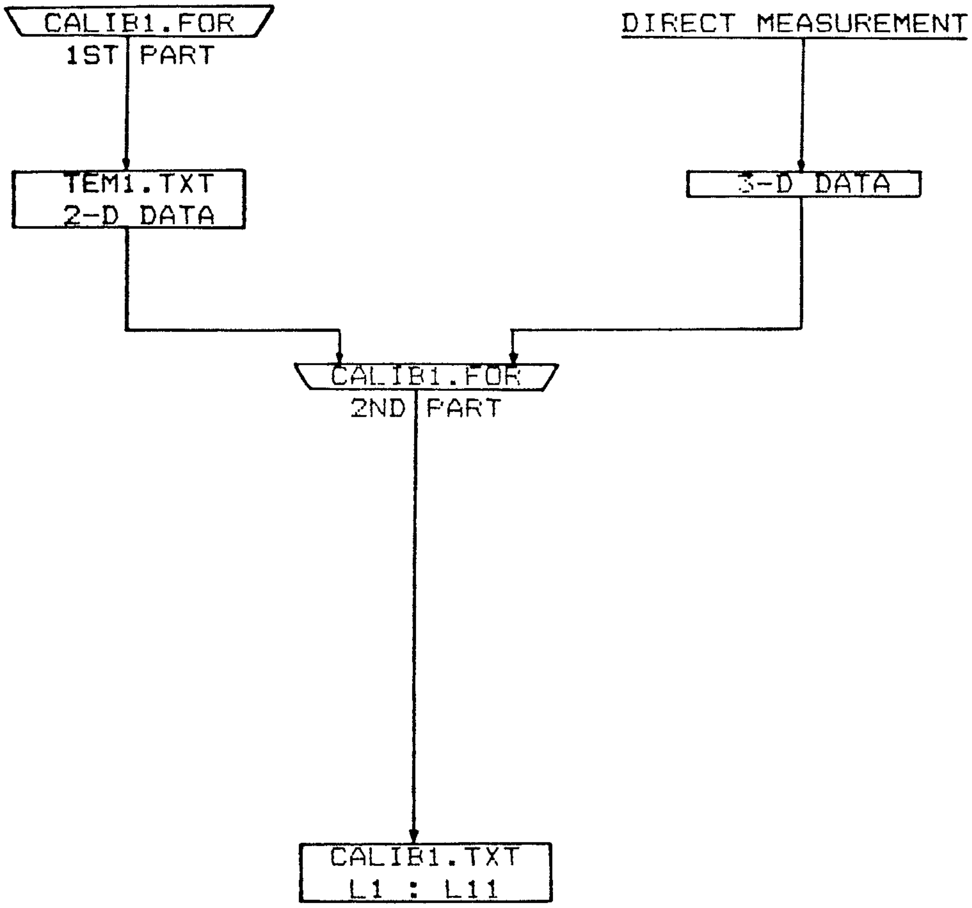
The next step is executing the second part of the program CALIB1.FOR and CALIB2.FOR. The input data for the second part are 2-D coordinates of the control markers which are read from the above mentioned files and the 3-D measured coordinates of control markers which are typed in by the operator. The 3-D data should be typed in the same order as the 2-D data for each image. The output of these two programs are the eleven calibration parameters for each camera which are stored in two data files: CALIB1.TXT and CALIB2.TXT.

This system of calibration is easy to use (compared to other systems of calibration) and there is no need of recalibration as long as the camera-related parameters are not changed. The flow chart for the above-mentioned steps is shown in Fig. 3.6.

3.2.2 ARM MOVEMENT RECORDING AND 2-D CALCULATION

To acquire movement data that can be used to determine the 3-D movement data of the limb, it is necessary that the two cameras are synchronized and also the beginning of recording be properly identified. This enables a proper match of two simultaneous frames. In order to synchronize the two cameras, one is synchronized internally and is used as a master and the other is synchronized externally and is used as a slave. The identification signal for the beginning of recording can be simply a fast or jerky hand movement by the subject.

Before starting to record arm movement, it is necessary to calculate the 2-D coordinates of reference markers. Because of vertical and horizontal shifts in the position of markers when each frame (image) is captured in the frame buffer, there is a need to use a reference marker for each camera. These markers are positioned on the edges of the activity table and in the field of view of each camera. By executing the programs IMAGE00.FOR for the first camera and the IMAGE01.FOR for the second camera, the XR and YR of the reference markers are calculated and stored in two files: OUTO.TXT AND OUTOO.TXT.



Note : Rectangle is used for data files and trapezoid is used for programs.

Fig.3.6 Calibration parameters calculation flow chart.

The next step is to put the markers on the arm. The subject wears a turtle neck shirt (black or dark blue). Seven spherical reflective markers are used, with the arrangement on the arm shown in Fig. 3.7. Fig. 3.8 shows the arrangement of plate, cup, spoon, fork, etc. At the beginning of arm movement recording, the subject is asked to move his arm rapidly in order to use this fast movement as an identification signal for the beginning of recording. Then the subject is asked to do the feeding task in a natural order and as natural as possible. Each task is recorded at least three times.

The recorded arm movement is then replayed frame-by-frame. Before processing each frame, the beginning of recording is identified and the frame counter of the VCR is reset to zero. This enables the operator to identify the beginning of each specific movement (i.e., drinking, eating with spoon, etc.) with the same frame number for both tapes. Each frame is then frozen and processed. For processing the stationary image and calculating the 2-D coordinates of seven markers in each frame, two programs are executed, one for each tape: IMAGE1.FOR and IMAGE2.FOR. Before executing these two programs three empty files are created for each program:

FRNO1.TXT for the frame number,

OUT1.TXT for the 2-D coordinates of the markers,

XYREF1.TXT for the 2-D coordinates of the reference marker.

The schematic diagram of the above-mentioned steps is shown in Fig. 3.9. The program IMAGE1.FOR and IMAGE2.FOR should be executed for each frame. However, typically only every fifth fram was used for the analysis. At the end, the data file OUT1.TXT contains the 2-D coordinated of 7 markers.

Fig. 3.7 Reflective marker arrangement on subject's arm.

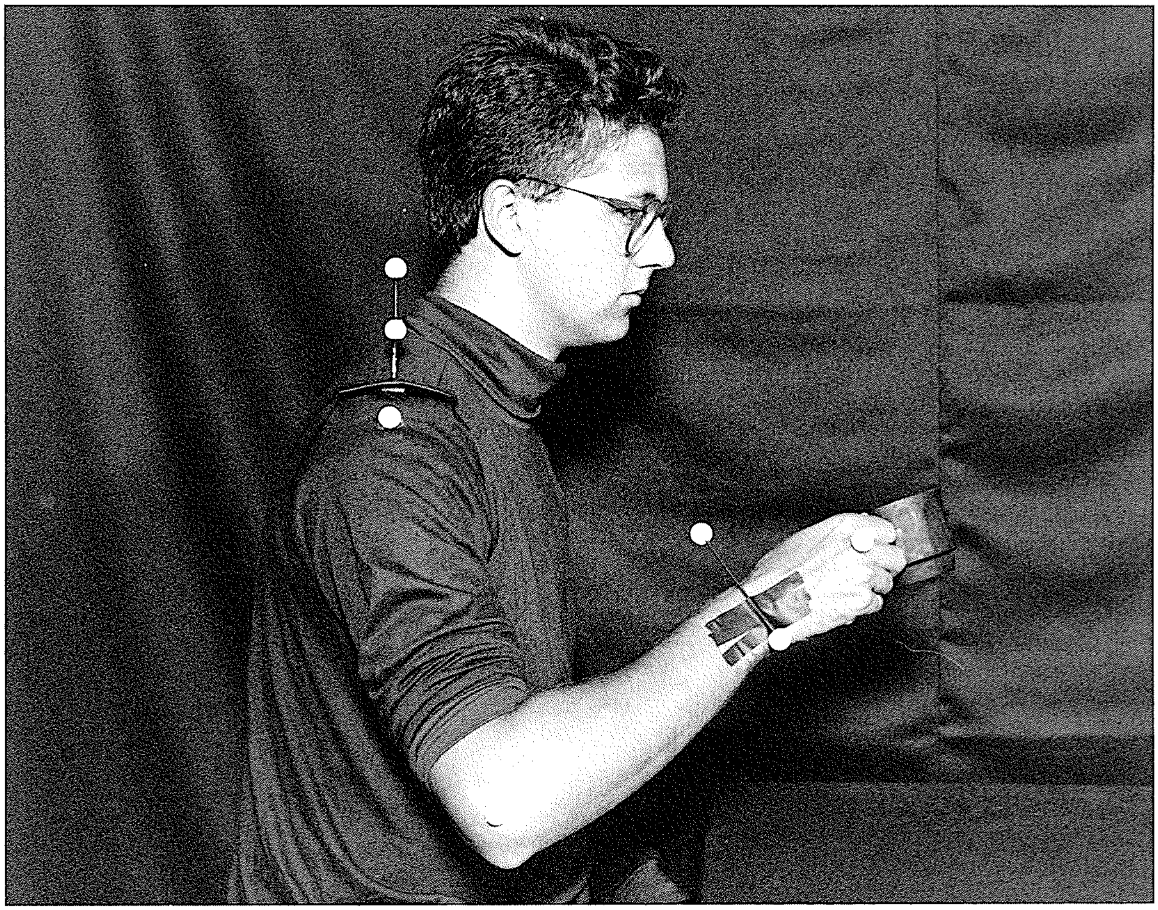


Fig. 3.8 Arrangement of plate, cup, etc., on the table of activity.

3.2.3 IDENTIFICATION OF MARKERS IN EACH FRAME

In order to calculate the 3-D coordinates of each marker based on its two 2-D coordinates, each marker in a frame is labelled by a number, and then the 2-D coordinates of the same marker in two simultaneous frame are used for its 3-D coordinate calculation. This identification process is called the tracking problem. Two programs are used for this purpose: TRACK1.FOR and TRACK2.FOR. The input data are the 2-D coordinates of markers from OUT1.TXT and OUT2.TXT. The order of markers in the first two frames are typed in by the operator. Here it should be emphasized that the marker order should be typed in by the operator in the same order as the 2-D data file. After identification of the markers in the first two frames by the operator, the tracking and identification of markers the remaining frames is done automatically by the computer. At the end a new data file for the 2-D coordinates of the markers is created. The order of the 2-D data for each frame in the new data file is from one to seven. This whole process is shown in Fig. 3.10.

3.2.4 3-D COORDINATE CALCULATION

Calculation of the 3-D marker coordinates is based on the new 2-D coordinate data file. The input data are: the 2-D coordinates of the markers: files NOUT1.TXT and NOUT2.TXT, and 11 calibtration parameters: files CALIB1.TXT and CALIB2.TXT. The output is the 3-D coordinates of the markers in each frame. The schematic diagram for the above-mentioned process is shown in Fig. 3.11.

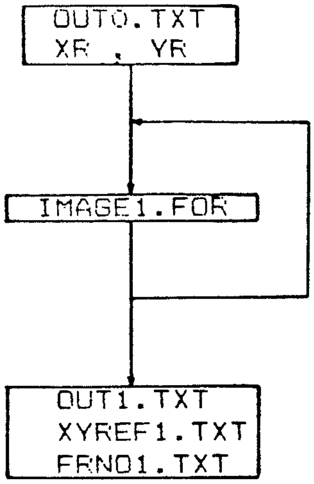


Fig.3.9 Marker 2-D coordinate calculation flow chart.

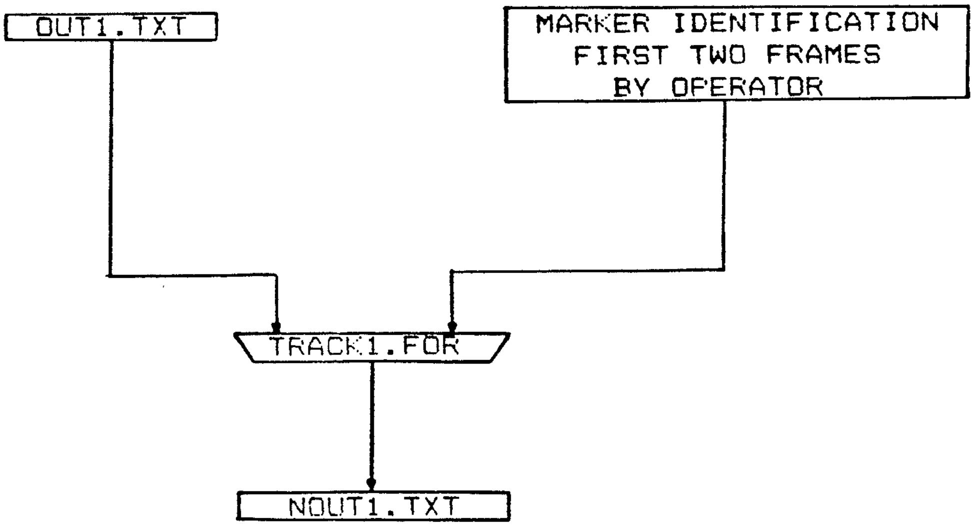


Fig.3.10 Marker identification flow chart.

3.2.5 EULER ANGLE CALCULATION FOR EACH JOINT

The final step is to calculate the Euler angles for the three joints: shoulder, elbow, and wrist. These angles show the amount of rotation with respect to the three orthogonal axes and can be interpreted as flexion-extension, abduction-adduction (or ulna deviation-radial deviation), and finally inward-outward rotation (or pronation-supination). The program for this calculation is ANGROT10.FOR. The input data is the 3-D coordinate and the output is the Euler angles for each joint. The schematic diagram in Fig. 3.12 shows this process.

3.2.6 STICK DIAGRAM PLOTTING

In order to provide a visual presentation of arm movement, two dimensional stick diagram can be plotted. They can be plotted for both the image and object planes. The first two are plotted in the camera image planes and are based on ordered 2-D coordinates of the markers. The second three are plotted in the three orthogonal planes of the fixed reference frame: XY, XZ, and YZ planes and are based on the 3-D coordinates of markers. The schematic diagram for these two cases are shown in Fig. 3.13.

3.3 SOFTWARE COMPONENTS OF THE SYSTEM

The complete list of program names for the 3-D measurement system for functional arm motion study is presented in Table 3.1. In this

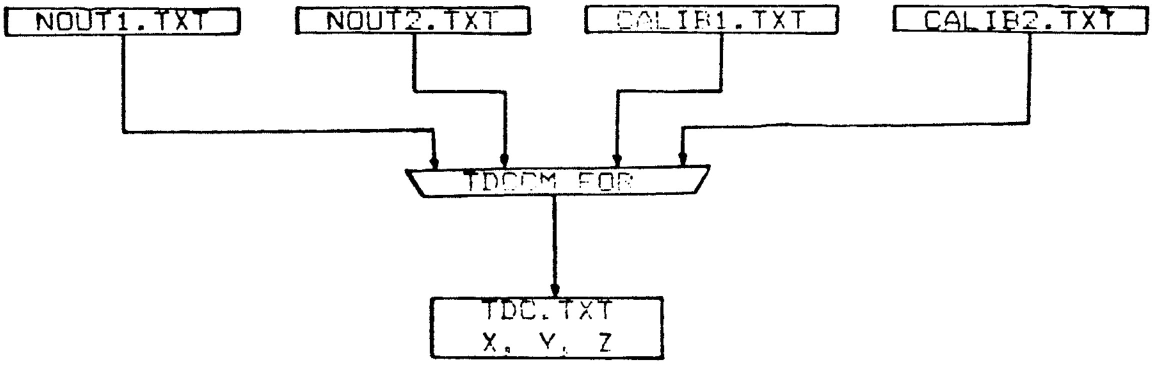


Fig.3.11 Marker 3-D coordinate calculation flow chart.

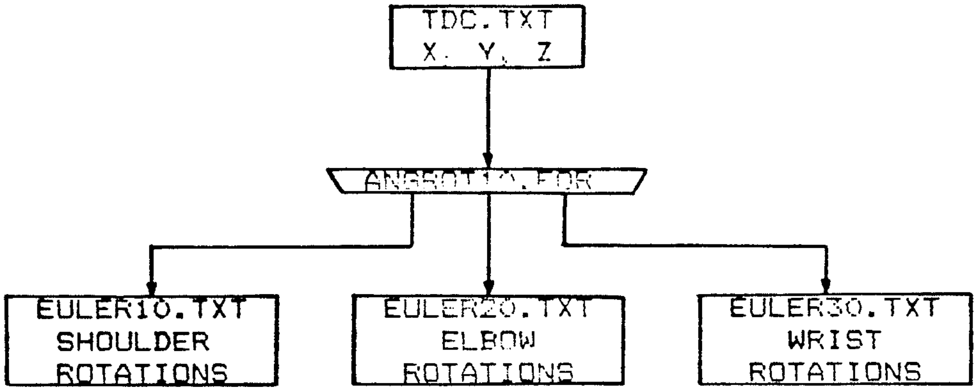


Fig.3.12 Euler angle calculation flow chart.

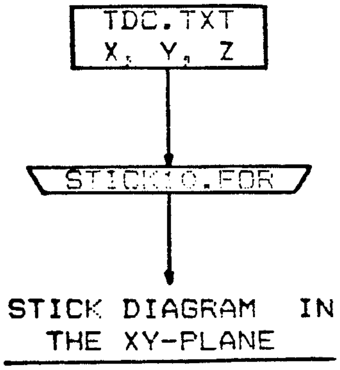


Fig.3.13 Stick diagram plotting flow chart.

section, different image processing techniques, algorithms and mathematical equations that are used in these programs are explained. The complete lists of the programs with sufficient comment statements are given in the Appendix (A).

TABLE 3.1. List of 3-D Measurement System Computer Programs

	Camera (1)		Camera (2)
(1)	CALIB1.FOR	SUB3.FOR	CALIB2.FOR
(2)	IMAGE0.FOR		IMAGE00.FOR
(3)	DATA1.FOR XYREF1.FOR FRNO1.FOR IMAGE1.FOR		DATA2.FOR XYREF2.FOR FRNO2.FOR IMAGE2.FOR
(4)	TRACK1.FOR		TRACK2.FOR
(5)		SUB4.FOR TDCCM.FOR	
(6)		ANGROT10.FOR	
(7)	STICK1.FOR	STICK10.FOR STICK20.FOR STICK30.FOR	STICK2.FOR

In general acquiring 3-D data from real object points via a stereometric system is done by the following steps:

- camera calibration,
- stereo matching (tracking and identification),

- multiple stereo views covering the whole object points,
- geometrical computations to determine the 3-D coordinates.

The final step is the Euler angle calculation which is done using acquired 3-D coordinates of the markers.

3.3.1 CAMERA CALIBRATION

The relationship between the 3-D coordinates in object space and the corresponding 2-D coordinates in the image space is essentially a perspective transformation [Duda et al. 1973, 24]. When this transformation is known, given the 3-D coordinates X, Y, and Z in object space, the corresponding 2-D coordinates of U and V in the image space can be found. Conversely, given the coordinates of U and V in the image space, the corresponding ray along which all the points satisfying this transformation must lie can be found. The elements of the transformation matrix are called calibration parameters.

There are several different calibration methods based on different camera models. The camera model used here is the one which is used in computer vision and computer graphics [Ballard, 1982, 25]. This camera model is called central projection, i.e. the image is an ideal central projection of the object-space onto the image-plane. Here, ideal means that the camera compound lens is free of optical distortion and thus the image is not deformed. Homogeneous coordinates are used for calibration of the above camera model [Lee, 1982, 26]. The process of developing the above-mentioned transformation using homogeneous coordinates is described below. For a more detailed mathematical treatment of homogeneous coordinate and its application to this specific camera model, refer to Duda et al. [Ibid, p.p.380-386]

In computer vision and computer graphics, homogeneous coordinates are widely used. The reason is that it allows many important geometric transformations to be represented uniformly and elegantly. The basic idea in using homogeneous coordinate for the ideal central projection camera model is to convert the non-linear transformation from 3-D object space to 2-D image space into a linear transformation in a different coordinate system, i.e., homogeneous coordinates. The important aspect of homogeneous coordinates is its redundancy: a point in Cartesian n-space is represented by a line in homogeneous (n + 1)-space, i.e., a unique point in Cartesian coordinates is represented by infinitely many homogeneous coordinates. Correspondence of these two coordinate systems is:

$$(X,\ Y,\ Z) \leftrightarrow (wX,\ wY,\ wZ,\ w) \tag{3.1}$$

where w is the extra redundant variable. In the special case of $w = 1$, this becomes:

$$(X,\ Y,\ Z) \leftrightarrow (X,\ Y,\ Z,\ 1) \tag{3.2}$$

Now, if homogeneous coordinates are applied to the 2-D image-space and the 3-D object-space, the result is:

$$\begin{aligned} &(U,\ V) \leftrightarrow (tU,\ tV,\ t) \\ &(X,\ Y,\ Z) \leftrightarrow (\ X,\ Y,\ Z,\ 1) \end{aligned} \tag{3.3}$$

The aim here is to find the transformation matrix from the 3-D homogeneous image space to the 4-D homogeneous object space and vice versa:

$$(X\ Y\ Z\ 1)\ [L] = (tU\ tV\ t)^T \tag{3.4}$$

Obviously this transformation takes the form of a 4 x 3 matrix:

$$(X\ Y\ Z\ 1)\begin{bmatrix} L_1 & L_5 & L_9 \\ L_2 & L_6 & L_{10} \\ L_3 & L_7 & L_{11} \\ L_4 & L_8 & L_{12} \end{bmatrix} = \begin{bmatrix} tU \\ tV \\ t \end{bmatrix}^T \qquad (3.5)$$

As it is seen there are three variables (U, V, t) and three equations. If t is eliminated in the first two, the result is:

$$L_1X + L_2Y + L_3Z + L_4 - L_9UX - L_{10}UY - L_{11}UZ - L_{12}U = 0$$

$$L_5X + L_6Y + L_{7Z} + L_8 - L_9Vx - L_{10}VY - L_{11}VZ - L_{12}V = 0 \qquad (3.6)$$

or:

$$U = \frac{L_1X + L_2Y + L_3Z + L_4}{L_9X + L_{10}Y + L_{11}Z + L_{12}}$$

$$V = \frac{L_5X + L_6Y + L_7Z + L_8}{L_9X + L_{10}Y + L_{11}Z + L_{12}} \qquad (3.7)$$

By simple scaling, L_{12} is equated to 1 and these two transformations become:

$$U = \frac{L_1X + L_2Y + L_3Z + L_4}{L_9X + L_{10}Y + L_{11}Z + 1}$$

$$V = \frac{L_5X + L_6Y + L_7Z + L_8}{L_9X + L_{10}Y + L_{11}Z + 1} \qquad (3.8)$$

Thus, it is possible to write two linear equations for each point (L_{12} = 1):

$$L_1X_i + L_2y_i + L_3Z_i + L_4 - L_9U_iX_i + L_{10}U_iY_i + L_{11}U_iZ_i = U_i$$

$$L_5X_i + L_6Y_i + L_7Z_i + L_8 - L_9V_iX_i + L_{10}V_iY_i + L_{11}V_iZ_i = V_i \qquad (3.9)$$

in which:

U_i, V_i: image coordinates of the i th point

X_i, Y_i, Z_i: object coordinates of the i th point

$L_1 - L_{11}$: calibration parameters.

(3.9) can be written in matrix form, and if it is written for n points, the resulting matrix equation is:

$$\begin{bmatrix} X_1 & Y_1 & Z_1 & 1 & 0 & 0 & 0 & 0 & -U_1X_1 & -U_1Y_1 & -U_1Z_1 \\ 0 & 0 & 0 & 0 & X_1 & Y_1 & Z_1 & 1 & -V_1X_1 & -V_1Y_1 & -V_1Z_1 \\ X_2 & Y_2 & Z_2 & 1 & 0 & 0 & 0 & 0 & -U_2X_2 & -U_2Y_2 & -U_2Z_2 \\ 0 & 0 & 0 & 0 & X_2 & Y_2 & Z_2 & 1 & -V_1X_2 & -V_2Y_2 & -V_2Z_2 \\ . & . & . & . & & & & & & & \\ . & . & . & . & & & & & & & \\ . & . & . & . & & & & & & & \\ . & . & . & . & & & & & & & \\ & & & & & & & & & & \\ X_n & Y_n & Z_n & 1 & 0 & 0 & 0 & 0 & -U_nX_n & -U_nY_n & -U_nZ_n \\ 0 & 0 & 0 & 0 & X_n & Y_n & Z_n & 1 & -V_nX_n & -V_nY_n & -V_nZ_n \end{bmatrix} \begin{bmatrix} L_1 \\ L_2 \\ L_3 \\ L_4 \\ L_5 \\ L_6 \\ L_7 \\ L_8 \\ L_9 \\ L_{10} \\ L_{11} \end{bmatrix} = \begin{bmatrix} U_1 \\ V_1 \\ U_2 \\ V_2 \\ . \\ . \\ . \\ . \\ \\ U_n \\ V_n \end{bmatrix} \tag{3.10}$$

In matrix form (3.10) becomes:

$$[P]_{2n \times 11} \, [L]_{11 \times 1} = [Q]_{2n \times 1} \tag{3.11}$$

In order to solve (3.11) and obtain eleven calibration parameters, at least eleven equations are needed, or in another words at least six control points are needed (only one equation for the last point is used). In order to prevent the problem of singularity, all eleven equations should be independent of each other or, i.e., the columns of matrix [P] should be linearly independent. This can be achieved by preventing the control points from being in the same plane, i.e., have non-coplanar control points. But in order to calculate eleven calibration parameters more accurately, it is logical to use more than eleven equations. In this project eight control markers are used (sixteen equations for eleven unknowns). Thus equation 3.11 becomes an overdetermined system of equations. The classical approach to the problem is to use a minimum-squared-error (MSE) criterion to solve the equations. It has been shown [Duda et al. 1973, 24; Wu et al. 1984, 27] that the MSE solution of (3.11) is obtained by multiplying the vecter [Q] by the Pseudo-inverse of matrix [P]. Note that for the overdetermined system of equations, matrix [P] is a non-square matrix and thus in order to solve (3.11), the pseudo-inverse matrix must be used. The solution is:

$$[L] = ([P]^T[P])^{-1}[P]^T[Q] \qquad (3.12)$$

where $([P]^T[P])^{-1}[P]^T = [R]$ is the pseudo-inverse matrix of [P].

The eleven calibration parameters can be expressed in terms of external and internal parameters of the camera. Conversely, external and internal parameters of the camera can be expressed in terms of the eleven calibration parameters. These camera parameters are:

- position and attitude of the camera, i.e., coordinates of the nodal point (x, y, z) and the orientation of the optical axis (nine direction cosines),

- principal distance of the camera,
- scale factor.

One very important internal parameter of the camera that was not considered in the ideal central projection camera model is systematic error caused by optical distortion. Abdel-Aziz and Karara [Abdel-Aziz et al. 1971, 28] developed a methodology that would allow application of stereo-photogrammetric techniques to situations in which nonmetric camreas, i.e., those in which the internal orientations are not known, would be used. This method is called the "direct linear transformation method" (DLT). Thus in their mathematical model, optical distortion (symmetrical lens distortion and asymmetrical lens distortion) are considered. DLT has been applied to 3-D cinematography and its accuracy has been studied for static and dynamic conditions [Miller et al. 1980, 29; Shapiro, 1978, 30; Walton, 1979, 31]. It is clear that if optical distortion parameters are omitted in this model, the resulting equations would be the same as 3.8. However, the ideal central projection camera model provides sufficient accuracy for the functional arm motion study and thus there is no need to use a sophisticated camera model.

3.3.2 3-D COORDINATE CALCULATION

One the calibratin parameters have been determined, equation 3.9 shows that each 2-D image yields two equations in the three unknowns, X_i, Y_i, Z_i. Thus to determine the 3-d coordinates requires at least one more equation. Physically this means that at least two cameras should be used in order to provide the minimum number of equations required. Of course it is possible and sometimes recommended to use multiple (more than two) cameras to get more accurate measurements.

When two cameras are used four equations for each point can be written based on the two sets of calibration parameters:

$$L_1X + L_2Y + L_3Z + L_4 - L_9U_1X - L_{10}U_1Y - L_{11}U_1Z - U_1 = 0$$
$$L_5X + L_6Y + L_7Z + L_8 - L_9V_1X - L_{10}V_1Y - L_{11}V_1Z - V_1 = 0$$

$$L_1'X + L_2'Y + L_3'Z + L_4' - L_9'U_2X - L_{10}'U_2Y - L_{11}'U_2Z - U_2 = 0$$
$$L_5'X + L_6'Y + L_7'Z + L_8' - L_9'V_2X - L_{10}'V_2Y - L_{11}'V_2Z - V_2 = 0 \qquad (3.13)$$

in which:

U_1, V_1: 2-D coordinates of the point in the 1st image

U_2, V_2: 2-D coordinates of the point in the 2nd image

X, Y, Z: 3-D coordinates of the point

L_1- L_{11}:Calibration parameters of the 1st camera

L_1'- L_{11}': Calibration parameters of the 2nd camera.

Rearranging the terms in (3.13) one obtains:

$$(L_1 - L_9U_1)X + (L_2 - L_{10}U_1)Y + (L_3 - L_{11}U_1)Z + (L_4 - U_1) = 0$$

$$(L_5 - L_9V_1)X + (L_6 - L_{10}V_1)Y + (L_7 - L_{11V_1})Z + (L_8 - V_1) = 0$$

$$(L_1' - L_9'U_2)X + (L_2' - L_{10}'U_2)Y + (L_3' - L_{11}'U_2)Z + (L_4' - U_2) = 0$$

$$(L_5' - L_9'V_2)X + (L_6' - L_{10}'V_2)Y + (L_7' - L_{11}'V_2)Z + (L_8' - V_2) = 0 \qquad (3.14)$$

In order to simplify these equations the following terms are defined:

$A_{11} \equiv L_1 - L_9U_1$
$A_{12} \equiv L_2 - L_{10}U_1$
$A_{13} \equiv L_3 - L_{11}U_1$
$A_{21} \equiv L_5 - L_9V_1$
$A_{22} \equiv L_6 - L_{10}V_1$
$A_{23} \equiv L_7 - L_{11}V_1$

$A_{31} \equiv L_1' - L_9'U_2$
$A_{32} \equiv L_2' - L_{10}'U_2$
$A_{33} \equiv L_3' - L_{11}'U_2$
$A_{41} \equiv L_5' - L_9'V_2$
$A_{42} \equiv L_6' - L_{10}'V_2$
$A_{43} \equiv L_7' - L_{11}'V_2$

$$B_1 \equiv U_1 - L_4 \qquad B_3 \equiv U_2 - L'_4$$
$$B_2 \equiv V_1 - L_8 \qquad B_4 \equiv V_2 - L'_8 \qquad (3.15)$$

Thus (3.14) is simplified to:

$$\begin{aligned} A_{11}X + A_{12}Y + A_{13}Z &= B_1 \\ A_{21}X + A_{22}Y + A_{23}Z &= B_2 \\ A_{31}X + A_{32}Y + A_{33}Z &= B_3 \\ A_{41}X + A_{42}Y + A_{43}Z &= B_4 \end{aligned} \qquad (3.16)$$

In matrix form:

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \\ A_{41} & A_{42} & A_{43} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{bmatrix} \qquad (3.17)$$

$$[\,A\,]\,[\,D\,] = [\,B\,] \qquad (3.18)$$

Again because there are three unknowns and four equations the pseudo-inverse must be used.

$$[X\ Y\ Z]^T = ([A]^T[A])^{-1}[A]^T[B] \qquad (3.19)$$

In summary, knowledge of the two 2-D coordinates of a point and the two sets of calibration parameters for the two cameras allows one to calculate the 3-D coordinates of the point (X, Y, Z).

3.3.3 IMAGE PROCESSING AND 2-D COORDINATES CALCULATION

As shown, the 3-D coordinate calculation of a point is based on the 2-D coordinates of the point (markers's centroid). In order to find the marker centroids in each frame, all the pixels which belong to a marker need to be identified and clustered. To do the clustering, a few simple techniques are used. In this section these simple techniques used to process the image are discussed. The object is to process the image as fast as possible and minimize the amount of data that should be stored. Note that each image of 512 by 512 needs 256 K bytes of storage space and takes 60 seconds to be processed. Using these simple techniques, data acquisition and data preprocessing from each frame takes less than 10 seconds and the final data is the seven 2-D coordinates of the seven markers, which needs a very small storage space.

After each frame (image) is captured in the frame buffer, the following image processing techniques are applied to obtain a marker centroid.

(1) Apply a threshold value. Basically the pixel values range from 0 (black) to 255 (white). By thresholding a black and white binary image is produced.

(2) Fast reading of the processed image. The image is 512 x 512. To read the 512 by 512 image pixel by pixel takes about 60 seconds for the PC. In order to reduce the reading time, the image is read in steps of 5, both vertically and horizontally (Fig. 3.14(a)). This reduces the reading time to less than 10 seconds. The image is read by the PC from left to right and from top to bottom. The value of 5 is based on the minimum size of the marker. If the marker is bigger, this value should be increased.

(3) Windowing. The next step is to put a window around the white pixels that were detected in the last step. The size of the window is two times the maximum size of the markers. In this project, the window size is 24 x 24 (Fig. 3.14(b)). It should be emphasised that all the

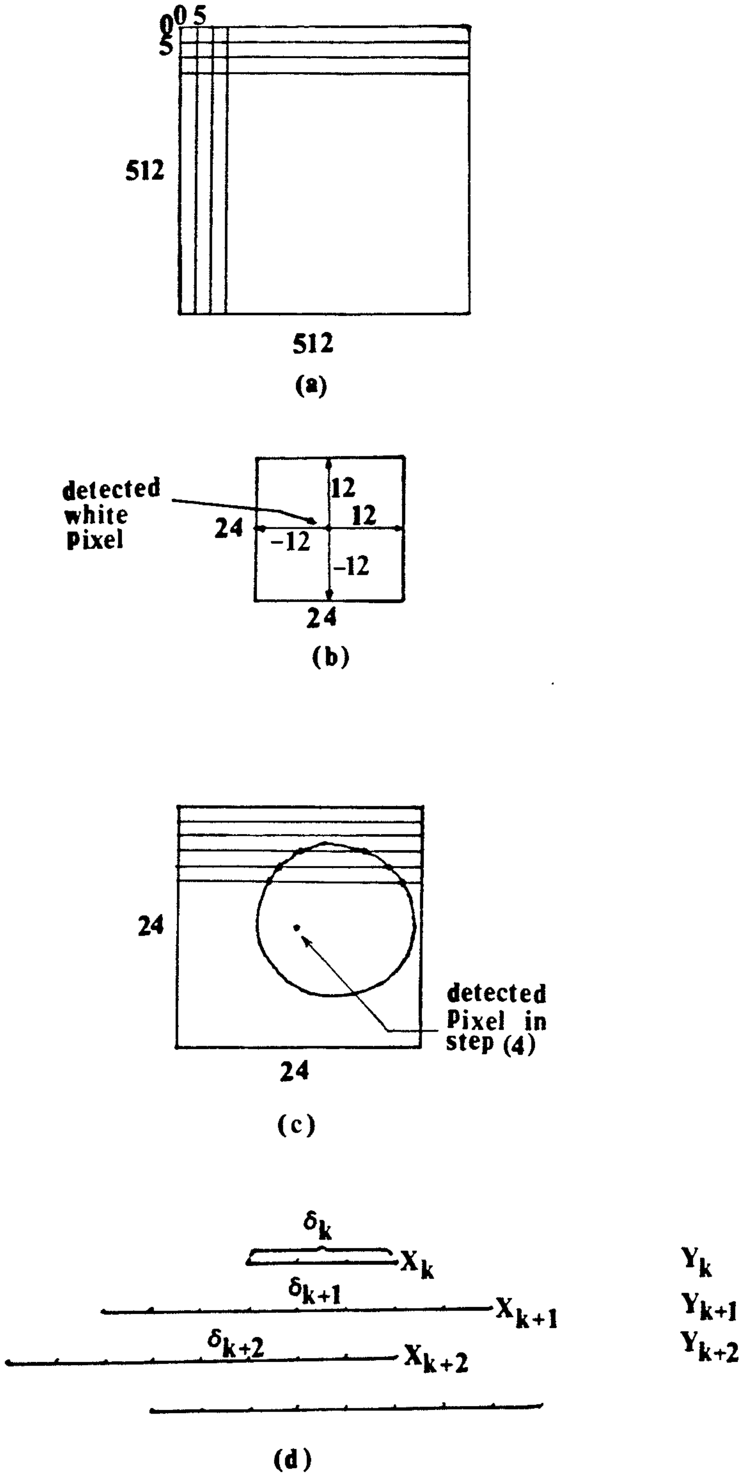


Fig.3.14 Schematic diagrams for image processing.

windows should be inside the 512 x 512 screen, otherwise the PC reads negative numbers and the whole program goes awry. Therefore the field of view of the cameras should be such that all the markers have a distance of at least 24 pixels from the screen edges.

(4) Detect the transition points in the window. The window is read pixel by pixel. The transition points from white to black or from black to white are deleted and thus the edge of the marker is determined (Fig. 3.14(c)).

(5) Marker centroid calculation. In order to calculate the centroid of each marker, the following simple equations are used (Fig. 3.14(d)):

$$X_C = \left[\sum_K (X_K - \frac{\delta_K}{2})\delta_K \right] \frac{1}{\sum_K \delta_K}$$

$$Y_C = \left[\sum_K Y_K \ \delta_K \right] \frac{1}{\sum_K \delta_K} \qquad (3.20)$$

(6) Elimination of repeated detected markers. Because there is a possibility that in step 4 more than one pixel of the same marker is detected, in the last part of the program, all the markers that are detected more than once are eliminated.

(7) Vertical and horizontal shifts. Because there is a possibility that the captured image in the frame buffer has a vertical or horizontal (or both) shift, the coordinates of the reference marker in the captured image is compared with the original coordinates of the reference marker and the vertical and horizontal differences are applied to the coordinates of the seven markers.

(8) Scattered noise in the image. To eliminate scattered noise (isolated white pixels) in the processed image, a simple condition is used to determine whether a detected marker is valid:

If $\sum \delta_k < 20$ eliminate the detected marker.

This condition is based on the fact that the minimum number of white pixels in each marker is 20.

In order to make the image processing more flexible, four interactive questions are used and these should be answered by operator. The first is choosing the threshold value. The second is to verify whether the processed image is acceptable or not (based on the choosen threshold value). The third and fourth are to choose the reading increment and window size. The output of the above-mentioned steps is the 2-D coordinates of the marker centriods.

3.3.4 TRACKING ALGORITHM

As explained before, in order to calculate the 3-D coordinates of a marker, the marker should be identified in the two simultaneous images. One important problem in tracking and identification of markers is the problem of disappearance and reappearance of markers. In this project, this problem has been prevented by:

- proper positioning of the two cameras,
- the choice of marker positions on the arm and the spherical marker shape,
- proper lighting,
- choice of arm movement (feeding tasks).

Tracking is thus reduced to the identification of a fixed number (i.e.,

7) of markers in each frame. Since the image is read by the PC from top to bottom, the preliminary 2-D coordinates of markers are ordered according to the y coordinate. If, for example, the stick diagrams of four markers in two frames are as shown in Fig. 3.15,

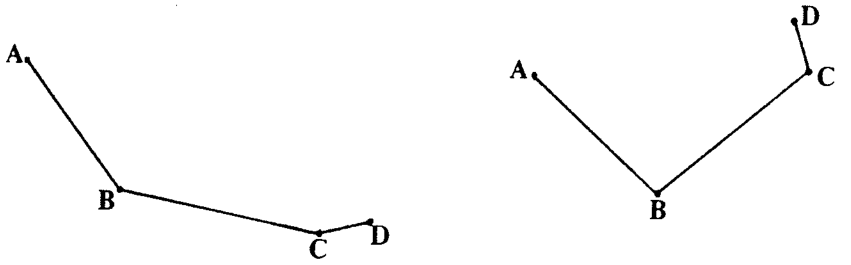


Fig. 3.15 Stick diagrams of two different frames.

then the marker order in the preliminary data file would be:

	FRAME NO.1	FRAME NO.2
1	A	D
2	B	C
3	D	A
4	C	B

It is clear that the marker order can change from one frame to the other. The aim in the tracking algorithm is to obtain the same order in all frames.

For the first two frames, the identification is done by the operator and the computer reads the order. For the third frame, simple two dimensional linear extrapolation is used. First the position of a marker in the third frame is estimated from:

$$x'_3 = x_1 + 2(x_2 - x_1)$$
$$y'_3 = y_1 + 2(y_2 - y_1) \qquad (3.21)$$

in which:

x_1, y_1: marker coordinates in the first frame

x_2, y_2: marker coordinates in the second frame

x'_3, y'_3: estimated marker coordinates in the third frame.

The estimated coordinates are then compared with all the marker coordinates in the third frame, and, based on the nearest neighbour criterion, the marker is identified in the third frame.

The identification of markers in subsequent frames (fourth, fifth, ...) is done by using a three point, 2-D linear least squares approximation i.e., the best straight line y = ax + b through the set of measured values is determined. The unknowns a and b are estimated by using following equations [Spencer et al. 1977, 32]:

$$a = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{n\sum x_i^2 - (\sum x_i)^2}$$

$$b = \frac{\sum y_i - a\sum x_i}{n} \qquad (3.22)$$

in which:

x_i, y_i: measured values

n: number of measured values.

For the specific case at hand, the result is:

$X = aF + b$

in which:

X: x coordinate of marker

F: frame number.

So for the fourth frame, the estimate for x is:

$$x'_4 = aF_4 + b \rightarrow x'_4 = 4\ a + b$$

where

$$a = \frac{3(1x_1 + 2x_2 + 3x_3) - (1 + 2 + 3)(x_1 + x_2 + x_3)}{3(1^2 + 2^2 + 3^2) - (1 + 2 + 3)^2}$$

$$a = \frac{-x_1 + x_3}{2}$$

$$b = \frac{(x_1 + x_2 + x_3) - a(1 + 2 + 3)}{3}$$

$$b = \frac{(x_1 + x_2 + x_3) - 6a}{3}$$

Thus the general estimation equation is:

$$x'_{n+3} = 4a_x + b_x$$

$$y'_{n+3} = 4a_y + b_y \tag{3.23}$$

in which:

$$a_x = \frac{-x'_n + x'_{n+2}}{2}$$

$$a_y = \frac{-y'_n + y_{n+2}}{2}$$

$$b_x = \frac{(x'_n + x'_{n+1} + x'_{n+2}) - 6a_x}{3}$$

$$b_y = \frac{(y'_n + y'_{n+1} + y'_{n+2}) - 6a_y}{3} \tag{3.24}$$

After the estimation of a marker's coordinates in the fourth frame, the estimate is compared to all measured coordinates in the fourth frame, and, based on the nearest neighbour criterion, the marker is identified in the fourth frame. The result of applying this tracking algorithm to preliminary 2-D data file will be the final ordered 2-D data file. Based on this data file identical markers in two simultaneous frames are matched and markers' 3-D coordinates are calculated.

3.3.4 EULER ANGLE CALCULATION

Major joints of the body generally have six degrees of freedom: three translational and three rotational. In this study, only rotational motion is considered. For anatomical purposes, the orientation of a segment of the arm is often defined by rotations in three orthogonal planes (saggital, frontal, and transverse), as well as the rotation about the longitudinal axis of the body segment. The most convenient and proper way of defining three rotational motions with respect to three orthogonal axes is to use Euler angles. Several different types of Euler angle systems have been used. The one that is used here is the type that has been widely used in aeronautical engineering and also in the analysis of missiles and other space vehicles [Greenwood, 1965, 34; Rosenberg, 1977, 35]. This type has also been used recently in the functional study of arm movement [Kinzel et al. 1983, 33; Chao et al. 1978, 13; Langrana, 1981, 11].

It should be noted that for 3-D rotations, the order of rotation about specified axis is extremely important in order to describe the joint motion uniquely. In Fig. 3.16, the order of rotations and the Euler angles are as follows:

- Rotation about the Z axis:

ϕ
$Z \rightarrow z'$
$X \rightarrow x'$
$Y \rightarrow y'$

- Rotation about the x´ axis

θ
$x' \rightarrow x''$
$y' \rightarrow y''$
$z' \rightarrow z''$

-Rotation about the y" axis:

ψ
$y'' \rightarrow y$
$x'' \rightarrow x$
$z'' \rightarrow z$

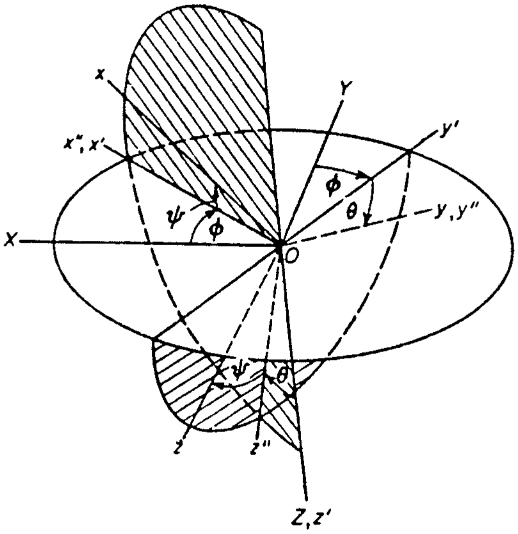


Fig. 3.16 The Eulerian angles.

These three rotations can be expressed by the following three matrix equations:

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

$$\begin{bmatrix} x'' \\ y'' \\ z'' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}$$

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \cos\psi & 0 & -\sin\psi \\ 0 & 1 & 0 \\ \sin\psi & 0 & \cos\psi \end{bmatrix} \begin{bmatrix} x'' \\ y'' \\ z'' \end{bmatrix}$$

Now if these three rotations are combined, the total transformation matrix is:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \cos\phi\cos\psi - \sin\phi\sin\theta\sin\psi & \sin\phi\cos\psi + \cos\phi\sin\theta\sin\psi & -\cos\theta\sin\psi \\ -\sin\phi\cos\theta & \cos\phi\cos\theta & \sin\theta \\ \cos\phi\sin\psi + \sin\phi\sin\theta\cos\psi & \sin\phi\sin\psi - \cos\phi\sin\theta\cos\psi & \cos\theta\cos\psi \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{3.25}$$

If $(\hat{i}, \hat{j}, \hat{k})$ are the unit vectors of the xyz orthogonal axes and $(\hat{I}, \hat{J}, \hat{K})$ are the unit vectors of the XYZ orthogonal axes, then (3.25) can be written in the following form:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \hat{i}.\hat{I} & \hat{i}.\hat{J} & \hat{i}.\hat{K} \\ \hat{j}.\hat{I} & \hat{j}.\hat{J} & \hat{j}.\hat{K} \\ \hat{k}.\hat{I} & \hat{k}.\hat{J} & \hat{k}.\hat{K} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{3.26}$$

If the transformation matrix in (3.26) is compared with the transformation matrix in (3.25), the following equations can be written:

$$\sin\theta = \hat{j}.\hat{K} \rightarrow \qquad \theta = \text{Arc sin }(\hat{j}.\hat{K})$$

$$\cos\phi\cos\theta = \hat{j}.\hat{J} \rightarrow \qquad \phi = \text{Arc cos }\left(\frac{\hat{j}.\hat{J}}{\cos\theta}\right)$$

$$\cos\theta\cos\psi = \hat{k}.\hat{K} \rightarrow \qquad \psi = \text{Arc cos }\left(\frac{\hat{k}.\hat{K}}{\cos\theta}\right) \tag{3.27}$$

On the other hand, the elements of the transformation matrix in (3.26) are the direction cosines of unit vectors i, j, and k in the XYZ frame of reference (Fig. 3.17):

$$\hat{j}.\hat{K} = \cos\gamma_2 = (Z_2 - Z_1)_j$$

$$\hat{j}.\hat{J} = \cos\beta_2 = (Y_2 - Y_1)_j$$

$$\hat{k}.\hat{K} = \cos\gamma_3 = (Z_2 - Z_1)_k$$

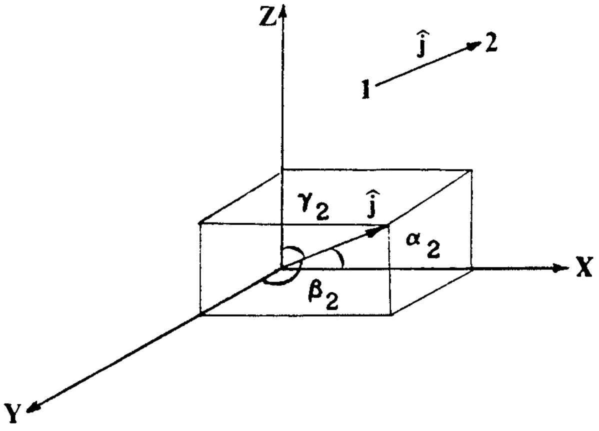


Fig. 3.17 Body axes unit vector directional cosines.

Thus, (3.27) can be written in the following final form:

$$\theta = \text{Arc sin}\left[(Z_2 - Z_1)_j\right]$$

$$\phi = \text{Arc cos}\left[\frac{(Y_2 - Y_1)_j}{\cos\theta}\right]$$

$$\psi = \text{Arc cos}\left[\frac{(Z_2 - Z_1)_k}{\cos\theta}\right] \tag{3.28}$$

To measure the rotational motion of an arm's different joints, the kinematic model has to be defined for each joint. It has been shown that there are three rotational motions in elbow and wrist joint [Chao et at. 1980, 19; Palmer et al. 1985, 23]. However due to the insignificant role of the third rotational motion of the elbow in general [Chao et al. 1980, 19] and in our study in particular, a two degree of freedom (rotation) model is defined for the joint.

For the shoulder a three-DOF spherical joint is used (Fig. 3.18). This kinematic model has been used for the human shoulder in many studies [Taylor et al. 1951, 36; Dempster, 1955, 37; Bahmink et al. 1963, 38; Steindler, 1964, 39; Bausso, 1969, 40; Risteen et al. 1970, 41]. The shoulder joint in this study is considered to have three rotations with respect to the three orthogonal axes. In anatomical terms these are:

- Flexion-Extension,
- Abduction-Adduction,
- Inward-Outward Rotation.

For the elbow, a two-DOF spherical joint is used (Fig. 3.18). This kinematic model has been used for the human elbow in a few studies [Taylor et al. 1951, 36; Taylor, 1954, 42; Dempster, 1955, 37]. Thus

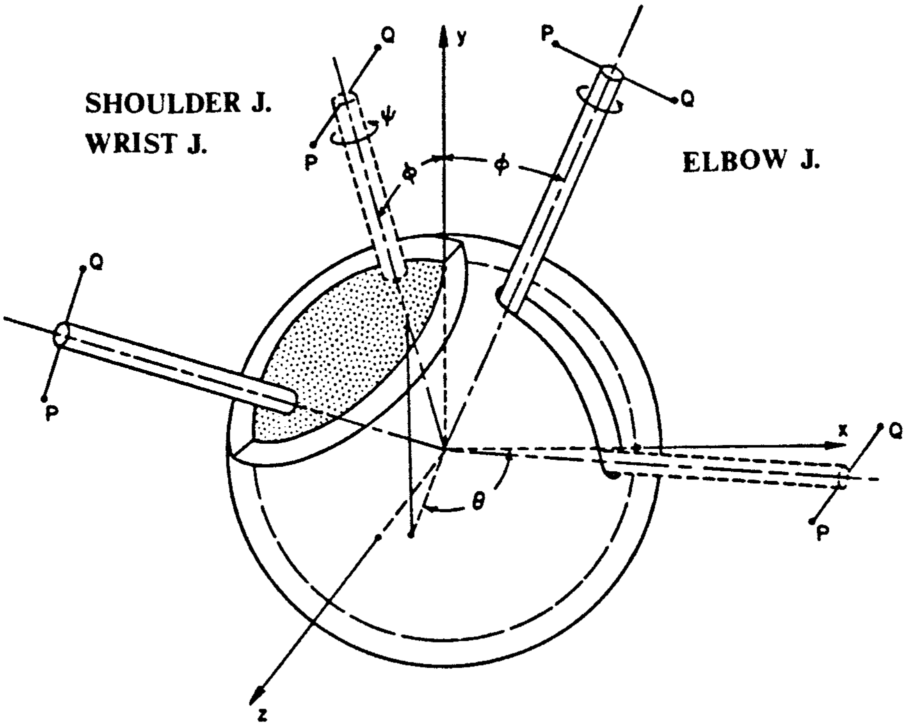


Fig.3.18 Kinematic model for shoulder,elbow,and wrist joints.

the elbow joint can have two rotations which are:

- Flexion-Extension
- Pronation-Supination.

At this joint, abduction-adduction of the elbow or in another words the carrying angle (rotation of ulna relative to radial bone at elbow) is omitted.

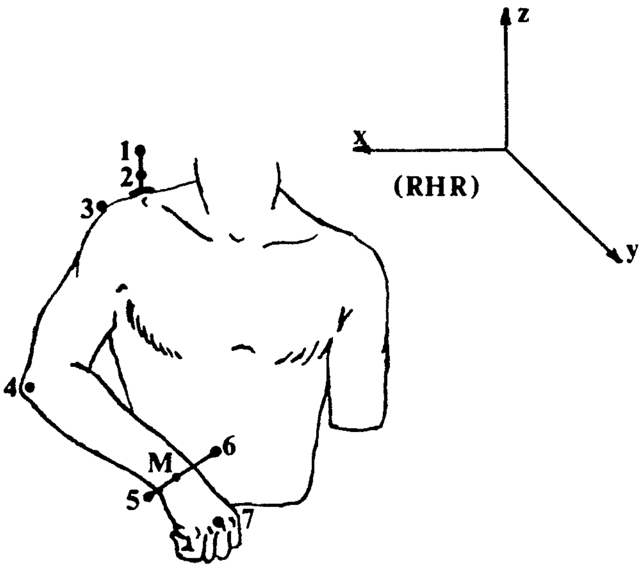
For the wrist, a three-DOF spherical joint is used (Fig 3.18). This kinematic model has also been used for human wrist before [Youm et al. 1979, 43]. In anatomical terms, these three rotations are defined as follow:

- Flexion-Extension
- Abduction-Adduction
  (ulna deviation, radial deviation)
- Inward-Outward Rotation

Thus altogether, in this study, the human arm has eight degrees of freedom and eight rotational motions are measured. In order to measure these eight rotational motions, seven markers are used as shown in Fig. 3.19. For each segment of the arm, one orthogonal body axis is defined. Therefore, three orthogonal body axes are defined for the upper body, forearm, and hand. A fourth orthogonal body axis system is also defined for the shoulder (Fig. 3.20). These orthogonal axes are defined as follows (RHR is used):

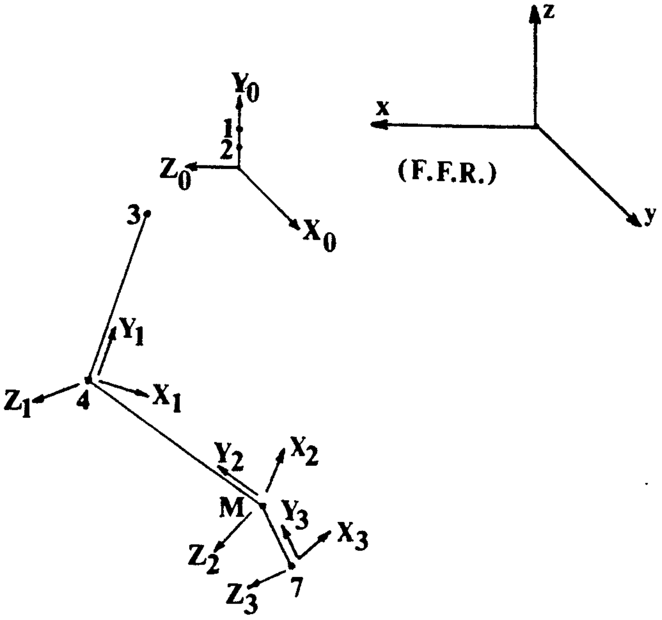
- shoulder:

$$\vec{y}_0 = \vec{21}$$
$$\vec{x}_0 = \vec{21} \times \vec{23}$$
$$\vec{z}_0 = \vec{x}_0 \times \vec{y}_0$$



Note : M is defined as a point in the middle of the wrist.

Fig.3.19 Markers arrangement on the human arm and fixed fixed frame of reference.



Note : F.F.R. : Fixed frame of reference.

Fig.3.20 Four orthogonal body axis and fixed frame of referance.

- upper arm:

$$\vec{y}_1 = \vec{43}$$
$$\vec{z}_1 = \vec{4M} \times \vec{43}$$
$$\vec{x}_1 = \vec{y}_1 \times \vec{z}_1$$

- forearm:

$$\vec{y}_2 = \vec{M4}$$
$$\vec{x}_2 = \vec{46} \times \vec{45} \quad \text{(palm up)}$$
$$\vec{z}_2 = \vec{x}_2 \times \vec{y}_2$$

- hand:

$$\vec{y}_3 = \vec{7M}$$
$$\vec{x}_3 = \vec{75} \times \vec{76} \quad \text{(palm up)}$$
$$\vec{z}_3 = \vec{x}_3 \times \vec{y}_3$$

It should be noted that due to the way z_1 and x_2 are defined, abduction-adduction at the elbow joint is prevented. These orthogonal body axis are shown schematically in Fig. 3.20.

The Euler angles of each body axis with respect to a fixed frame of reference can be calculated by using equations (3.28). These give the rotation of each body segment (upper arm, forearm, and hand) with respect to the fixed frame of reference. For joint rotation, the relative motion of the body axes with respect to each other should be calculated. The absolute rotations are defined as follow:

- shoulder: $[E_0] = [T_0][E]$
- upper arm: $[E_1] = [T_1][E]$
- forearm: $[E_2] = [T_2][E]$
- hand: $[E_3] = [T_3][E]$ (3.29)

in which:

$[E]$: unit vectors of fixed frame of reference,

$[E_i]$: body axes unit vectors,

$[T_i]$: transformation matrix.

The joint rotations (relative) are defined as follows:

- shoulder joint:

$$[E_1] = [T_1][T_0]^{-1}[E_0] \rightarrow [E_1] = [R_1][E_0]$$

- elbow joint:

$$[E_2] = [T_2][T_1]^{-1}[E_1] \rightarrow [E_2] = [R_2][E_1]$$

- wrist joint:

$$[E_3] = [T_3][T_2]^{-1}[E_2] \rightarrow [E_3] = [R_3][E_2] \tag{3.30}$$

in which $[R_i]$ is the relative transformation matrix. Thus by calculating relative transformation matrices $[R_i]$, Euler angles for each joint can be calculated easily using equation 3.28.

CHAPTER 4

FUNCTIONAL ARM MOTION STUDY

The previous two chapters discussed arm motion classification and explained a new 3-D measurement system developed for functional arm motion study. In this chapter, based on the classification of arm motion, the 3-D measurement system is applied to study three important ADL. A summary of collected data is presented and an analysis of acquired data is given. Also the static and dynamic error of the system is discussed.

4.1 MATERIALS AND METHOD

This section explains the materials used to study a few functional arm motions and the overall experimental method.

Ten subjects were used in this experiment. All were healthy, right-handed males, ranging in age from 20 - 29 year and in height from 167 to 185 cm.

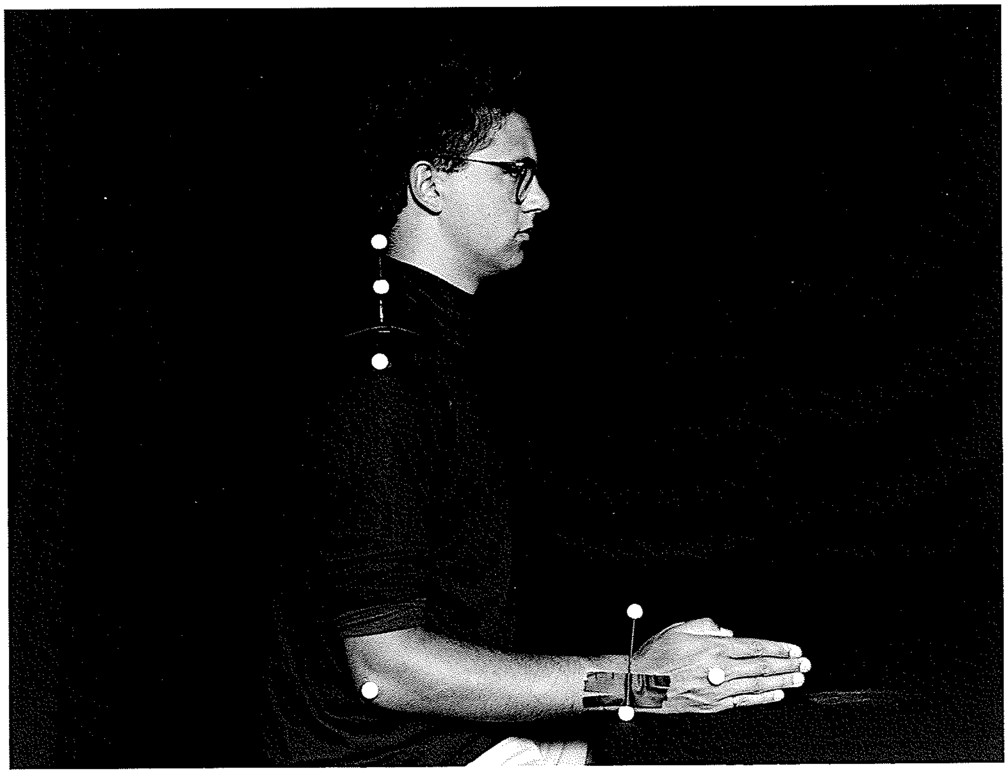
Three highly important ADL were chosen to be performed by the subjects. These were three feeding tasks: drinking from a cup, eating with a fork, and eating with a dessert spoon. To provide different degrees of consistency the drink and food consisted of orange juice, muffin, and pudding (or yogurt).

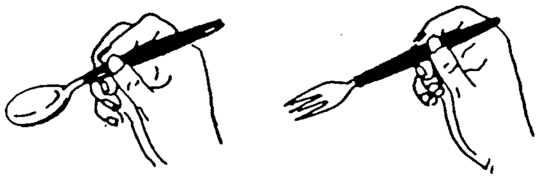
Before the subject performed the experiment, the purpose and the procedure of the experiment was explained. Then the subject was asked to wear a turtle neck shirt, and seven reflective spherical markers were put on the arm as explained in Chapter 3. An adjustable chair was used in order to adjust the chair height for the subject. The subject was asked to sit upright and flex his elbow to 90 degrees. The chair height then was adjusted so that the subject's forearm almost touched the table of activity. This height was a comfortable height for the subject and was used during the whole experiment.

To calibrate the seven markers, the subject was asked to fix his arm in the standard position: 90 degrees of elbow flexion and forearm neutral rotation (see Fig. 4.1). The arm's standard position was checked by visual observation. The result of this calibration was the initial deviation of the eight joint rotations. The subject would keep his arm in the standard position for 10 - 15 seconds and then perform drinking, eating with the fork, and eating with the spoon, respectively. Each task was done at least three times. The subject was asked to perform these tasks as naturally as possible.

Before performing each task, in order to identify the simultaneous frames for both recorded tapes, the subject moved his hand up and down rapidly. The returning position of the hand was used for identification and thus subsequent simultaneous frames could be counted by the VCR frame counter and easily identified. The overall time required to prepare the subject and perform the tasks was less than 10 minutes. Another important point that was considered in performing the eating tasks was the type of grip. The subject was asked to handle the fork or dessert spoon in the standard web-of-thumb grip.

Fig. 4.1 The standard arm position.





Dessert Spoon
Web-of-thumb grip

Serving fork
Web-of-thumb grip

Fig. 4.2 Type of Grip

This is one of the most frequent types of grip for eating [Sperling et al. 1977, 1].

When the recorded images were processed, two more factors were considered in order to standardize the whole experiment. First, the beginning and end points of each task had to be the same for different subjects; second only data from trials that were performed smoothly and without time lag or pause were processed.

The sampling frequency of recorded images for processing was very important. Some subjects did different feeding activities faster than the others. So in order to get sufficient information, it was necessary to use adaptive sampling. It was found that every 5 frames (which is equal to one sixth of a second) was a sufficient sampling frequency.

4.2 ANALYSIS OF COLLECTED DATA

The detailed collected data for ten subjects are given in Appendix (C), Tables 1 to 18. These cover the seven rotations for the three feeding tasks. The mean and standard deviation of minimum and maximum rotations and the resulting arcs (i.e., maximum rotation minus minimum rotation) also were calculated and are presented. A summary of the data is given in Tables 4.1 and 4.2. Table 4.1 shows the eight rotations without taking the initial deviation into account while in Table 4.2, the initial deviation is taken into account.

The mean and S.D. of the performance time for three feeding tasks and the average number of processed frames (based on a sampling frequency of 6 frames per second) is given in Table 4.3. On the average drinking with a cup took 2.62 sec., eating with a fork took 1.95 sec. and eating with a spoon took 2.31 sec. One interesting point that can be concluded from the data is the relationship between performance time and the degree of consistency (viscosity) of the food. Food with lower consistency takes longer to load and bring to the mouth! Eating food with low consistency requires a more accurate control and lower arm motion speed to prevent spilling. This aspect should be considered in developing preprogrammed feeding motions.

In order to understand and analyze the data in Tables 4.1 and 4.2, first an explanation should be given about the physical meaning of the numbers. Based on the definition of the four body axes for the shoulder, upper arm, forearm, and hand in Chapter 3, the meaning of the calculated angles ϕ, θ, and ψ (output of program ANGROT.FOR) in clinical terms are:

TABLE 4.1. AVERAGE ARM JOINT ROTATION DATA FOR THREE FEEDING TASKS.
(SUMMARY OF TABLES 1-9 IN APPENDIX C)

JOINT ROTATION		DRINKING WITH A CUP MIN.	MAX.	ARC	EATING WITH A FORK MIN.	MAX.	ARC	EATING WITH A SPOON MIN.	MAX.	ARC	INITIAL DEV.
SHOULDER											
FLEXION	MEAN	21.4	48.8	27.4	16.3	40.7	24.4	13.3	41.6	28.3	-5.6
	S.D.	(7.4)	(19.4)	(13.9)	(5.8)	(13.4)	(9.1)	(8.3)	(15.1)	(10.0)	
ABDUCTION	MEAN	-31.0	-49.5	18.5	-25.4	-37.0	11.6	-25.0	-40.2	15.2	-18.3
	S.D.	(7.6)	(9.4)	(9.5)	(8.0)	(6.9)	(2.6)	(8.2)	(7.1)	(7.2)	
IN. ROTATION	MEAN	13.0	31.2	18.2	12.9	25.9	13.0	12.7	24.6	11.9	-7.8
	S.D.	(7.7)	(14.2)	(8.0)	(11.1)	(11.9)	(2.2)	(15.8)	(15.2)	(5.1)	
ELBOW											
FLEXION	MEAN	78.3	135.9	57.6	100.6	129.0	28.4	107.9	129.9	22.0	-6.7
	S.D.	(6.6)	(3.3)	(5.2)	(9.0)	(5.5)	(5.3)	(10.5)	(6.8)	(7.9)	
PRONATION	MEAN					39.3			24.0		-1.2
	S.D.					(7.5)			(17.1)		
SUPINATION	MEAN	-2.3	-30.0	27.7		57.7	97.0		57.6	81.6	
	S.D.	(5.1)	(9.3)	(8.9)		(8.0)	(8.8)		(5.6)	(17.5)	
WRIST											
EXTENSION	MEAN	-3.0	-16.4	13.4	-13.7	-28.1	14.4	-18.1	-30.9	12.8	-10.5
	S.D.	(3.9)	(8.0)	(6.2)	(7.7)	(6.4)	(3.8)	(6.9)	(7.4)	(4.1)	
ULNAR DEV.	MEAN	11.1	18.9	7.8		6.0			7.0		-2.8
	S.D.	(6.3)	(7.1)	(3.7)		(10.6)			(8.8)		
RADIAL DEV.	MEAN					-2.0	8.0		-1.6	8.6	
	S.D.					(8.9)	(3.0)		(8.8)	2.4	
ROTATION (IN.-OUT.)	MEAN	0.5	3.0	2.5	0.8	2.9	2.1	0.7	3.2	2.5	-1.0
	S.D.	(0.9)	(1.7)	(1.6)	(1.1)	(2.5)	(1.6)	(1.2)	(1.6)	(0.8)	

TABLE 4.2. AVERAGE ARM JOINT ROTATION DATA FOR THREE FEEDING TASKS.
TAKING INITIAL DEVIATION INTO ACCOUNT
(SUMMARY OF TABLES 10-18 IN APPENDIX C)

JOINT ROTATION		DRINKING WITH A CUP			EATING WITH A FORK			EATING WITH A SPOON		
		MIN.	MAX.	ARC	MIN.	MAX.	ARC	MIN.	MAX.	ARC
SHOULDER										
FLEXION	MEAN	15.8	43.2	27.4	10.7	35.1	24.4	7.8	36.1	28.3
	S.D.	(4.4)	(16.3)	(13.9)	(5.2)	(11.9)	(9.1)	(7.7)	(13.7)	(10.0)
ABDUCTION	MEAN	-12.7	-31.2	18.5	-7.1	-18.6	11.5	-6.6	-21.8	15.2
	S.D.	(7.7)	(9.2)	(9.5)	(7.8)	(6.0)	(2.6)	(9.9)	(7.1)	(7.2)
IN. ROTATION	MEAN	5.2	23.4	18.2	5.1	18.1	13.0	4.9	16.8	11.9
	S.D.	(8.0)	(12.0)	(8.0)	(9.8)	(10.0)	(2.2)	(12.0)	(11.9)	(5.1)
ELBOW										
FLEXION	MEAN	71.6	129.2	57.6	93.8	122.2	28.4	101.2	123.2	22.0
	S.D.	(5.9)	(2.5)	(5.2)	(6.0)	(3.6)	(5.3)	(8.1)	(5.0)	(7.9)
PRONATION	MEAN					38.2			22.9	
	S.D.					(7.8)			(14.6)	
SUPINATION	MEAN	3.5	31.2	27.7		58.8	97.0		58.7	81.6
	S.D.	(7.2)	(11.1)	(8.9)		(7.8)	(8.8)		(5.8)	(17.5)
WRIST										
EXTENSION	MEAN	7.5	-5.9	13.4	-3.2	-17.6	14.4	-7.6	-20.4	12.8
	S.D.	(6.1)	(8.3)	(6.2)	(8.2)	(7.2)	(3.8)	(9.0)	(8.7)	(4.1)
ULNAR DEV.	MEAN	8.3	16.1	7.8		3.2			4.2	
	S.D.	(6.4)	(7.2)	(3.7)		(8.2)			(6.2)	
RADIAL DEV.	MEAN					-4.8	8.0		-4.4	8.6
	S.D.					(6.7)	(3.0)		(5.9)	2.4
ROTATION (IN.-OUT.)	MEAN	-0.5	2.0	2.5	-0.2	1.9	2.1	-0.3	2.2	2.5
	S.D.	(0.8)	(1.7)	(1.6)	(1.0)	(2.2)	(1.6)	(1.0)	(1.3)	(0.8)

TABLE 4.3. Performance Time (Sec.)

Type of Task	Mean	S.D.	Average no. of Processed frames
Drinking with a cup	2.62	11.9	16
Eating with a fork	1.95	15.6	13
Eating with a spoon	2.31	14.6	15

Shoulder:

$\phi > 0$: Flexion

$\phi < 0$: Extension

$\theta > 0$: Adduction

$\theta < 0$: Abduction

$\psi > 0$: Inward Rotation

$\psi < 0$: Outward Rotation

Elbow:

$\phi > 0$: Flexion

$\psi > 90°$: Pronation (Forearm)

$\psi < 90°$: Supination (Forearm)

Wrist:

$\phi > 0$: Flexion

$\phi < 0$: Extension

$\theta > 0$: Ulnar Deviation

$\theta < 0$: Radial Deviation

$\psi > 0$: Inward Rotation

$\psi < 0$: Outward Rotation

In all the tables, absolute values for forearm pronation and supination are given, i.e., if the calculated angle is $\psi = 135°$ or 65°, the table would have 45°pronation or 35° supination respectively.

In order to analyze and evaluate the calculated joint rotations for different tasks in this study, all the available and published data by other research groups are tabulated in Table 4.4. For proper comparison it should be pointed out that for the shoulder joint there is no accurate data available. Only one paper [Davis, 1977, 2] reported

TABLE 4.4. SUMMARY OF AVAILABLE DATA ON FEEDING ACTIVITY.

COLUMN NO. JOINT ROTATION		(1) NORMAL RANGE	(2) DRINKING (GLASS) MIN.	MAX.	ARC	(3) DRINKING (CUP) MIN.	MAX.	ARC	(4) EATING (FORK) MIN.	MAX.	ARC	(5) EATING (FORK) MIN.	MAX.	ARC	BREAKF. RANGE	(6) LUNCH RANGE	DINNER RANGE
SHOULDER																	
FLEXION	MEAN	165.0													30	30	30
	S.D.	(5.0)															
EXTENSION	MEAN	57.3													0	0	0
	S.D.	(8.1)															
ABDUCTION	MEAN	182.7															
	S.D.	(9.0)															
ADDUCTION	MEAN	50															
IN. ROTATION	MEAN	68															
OUT. ROTATION	MEAN	68															
ELBOW																	
FLEXTION	MEAN	140.5	44.8	130.0	85.2	42	131	89	85.1	128.3	43.2	87	133	46	80-130	40-130	0-130
	S.D.	(4.9)				(9)	(6)					(14)	(8)				
EXTENSION	MEAN	0.3															
	S.D.	(2.7)															
PRONATION	MEAN	75.0		10.1			11			10.4			6		90	90	90
	S.D.	(5.3)					(13)						(30)				
SUPINATION	MEAN	81.1		13.4	23.5		16	27		51.8	62.2		56	62	10	15	20
	S.D.	(4.0)					21						(16)				
WRIST						CENTROID						CENTROID					
FLEXION	MEAN	74.8													80 (?)	15	15
	S.D.	(6.6)															
EXTENSION	MEAN	74.0	11.2	24.0	12.8	19			9.3	36.5	27.2	32			40	45	45
	S.D.	(6.6)															
ULNAR DEV.	MEAN	35.3										7					
	S.D.	(3.8)															
RADIAL DEV.	MEAN	21.1				0											
	S.D.	(4.0)															

shoulder flexion-extension data (column 6) based on 9 subjects. These data are not accurate because they are based only on visual observations and furthermore it is for feeding as a whole. They are good indicators, however, as a general range for feeding activity.

For the elbow joint, there are two references. The first [Morrey et al. 1981, 3] (column 2) gives data for drinking with a glass; the second reference [Chao et al. 1980, 4] (column 3) provides data for drinking with a cup. The former study is based on 33 subjects (18 female) and the latter on 15 male subjects. Also, the latter report gives standard deviations, which are important for comparison. These two papers also give data for eating with a fork (column 4 and 5 respectively). All the measurements were done by using a triaxial electrogoniometer.

For the wrist joint, there are also two papers. The first [Brumfield et al. 1984, 5] used a uniaxial electroganiometer and gives wrist flexion-extension for drinking with a glass and eating with a fork (column 2 and 4) and is based on 19 subjects. The second [Palmer et al. 1985, 6] provided two wrist joint rotations using a triaxial electrogoniometer. The data are for drinking with a cup and eating with a fork and were based on 10 subjects (column 3 and 5).

It should be noted that there is no published data on eating with a spoon. Finally the normal range of arm joint rotations is given in the first column [Boone et al. 1979, 7; AAOS, 1965, 8]. This provides a general indication for maximum arm joint rotations.

The initial deviation of different arm joint rotations, which is based on the standard position, is given in the last column of Table 4.1. This is the average for ten. subjects. Basically the effect of the initial deviation is to shift the range of joint rotations. As an example for shoulder flexion the initial deviation was -5.6° and thus it shifted the shoulder flexion range from 21.4° - 48.8° to 15.8° - 43.2°. The S.D. of joint rotation is also effected by the initial deviation. For the same example the S.D. for minimum and maximum rotations decreased from 7.4 and 19.4 to 4.4 and 16.3, respectively. The overall effect of taking initial deviation into account is the reduction of S.D. for different joint rotations, which in fact shows its positive effect (i.e., more consistent and less variable) on collected data.

Here it should be emphasized that because of the lack of accurate checking of the standard position for each subject, the collected initial deviation data were not accurate. Through close evaluation and checking of all the data and also the recorded tapes, it was concluded that the initial deviation for wrist extension was not correct (-10.5°). Thus, the wrist extension data without taking the initial deviation into account (Table 4.1) is used for analysis. Note that -10.5° is the largest recorded deviation (except for shoulder abduction which because of the positions of the markers no. 3 and 4, is clearly acceptable) and also that it has an increasing not decreasing effect on S.D. For the rest of collected data, overall it is concluded that the data in Table 4.2 is correct and may be used for analysis.

Comparison of the collected data with the normal range of arm joint rotations (Table 4.4, column 1) shows that all of these data are within normal range. Since for shoulder joint rotations there is no accurate data to compare with, these data are analyzed by themselves. The first important aspect that these data show is that the range (i.e., minimum and maximum joint rotations) and the arc (i.e., maximum joint rotation minus minimum joint rotation) for eating with a fork and eating with a spoon are very close. The second important aspect is the difference of arc and especially the range for the drinking task as compared to the other two tasks; it has a larger arc and higher range of rotation. This is due to the larger distance between the cup and the subject's body and to the smaller distance between the cup and the subject's mouth as compared to the spoon or fork. The third important aspect is that for these tasks only flexion, abduction and inward rotation are required, thus there is no need to provide extension, abduction or outward rotation. Overall the required arc and range for the three tasks are:

<u>SHOULDER</u>:

	Min.	Max.	Arc
- Flexion	5	45	40
- Abduction	-5	-30	25
- In. Rotation	5	25	20

For the elbow joint there are accurate data to compare the collected data with. Starting from elbow flexion for drinking with a cup (the data for glass and cup are almost identical), it is seen that the maximum rotation is identical (130°), but the minimum rotation is different (71° versus 42°). Two factors caused this difference. First, in this study some of the subjects used large forward movement of their trunk and head when performing these tasks. This is the main factor. The second factor is the cup position with respect to subject's body. With the increase ofdistance between cup and subject's body, a smaller flexion angle is required and, accordingly, a larger flexion arc is needed. This shows an important aspect of arm movement: it is possible to compensate for a large amounts of elbow flexion with trunk and head forward movement. All of the above discussion is also valid for eating with a fork. There is no comparison data for eating with a spoon.

For forearm pronation-supination the following points can be said. When drinking with a cup, the arc is identical (27°), but the range is different. The data in this study shows that only supination ranging from 3.5° to 31.2° is present, while column (3) in Table 4.4 shows 11° pronation and 16° supination. This latter range is more logical and corresponds to the actual pattern of drinking with a cup. The reason for this range difference is basically related to the definition of the neutral position of the forearm. Morrey [Morrey et al. 1981, 3] gave this definition as: "neutral rotation defined as the extended thumb being coplanar with the humerus". This standard position is shown in Fig. 4.3.

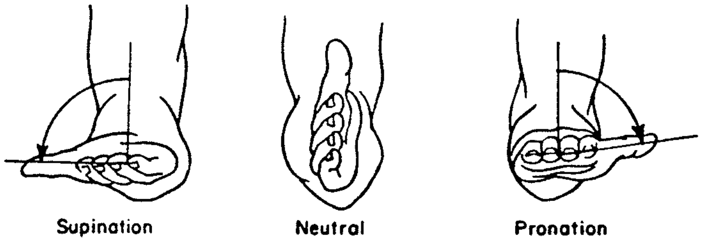


Fig. 4.3 Forearm Neutral Position

In this study, the forearm neutral position was determined by general observation without any specific criterion as was the case in the above mentioned study. So instead of having positive forearm initial deviation (approximately 14°), a negative initial deviation (-1.2°) was estimated. This indicates once again the importance of accurately defining the standard position and the need to accurately check the standard position during the experiment.

In the case of feeding with a fork the supination is very close (58°). But pronation and thus the arc is not the same. It is clear and can be checked easily by watching the recorded motion in the slow motion mode that the amount of pronation is much larger than the reported 6° in column 5 (Table 4.4). Some factors that might cause small pronation can be the grip type, whether the fork is used in the usual manner or as a spoon, and finally the definition of the beginning and the end of feeding with the fork. In this study the web-of-thumb grip was used. The fork was used in the usual manner and thus at the time of loading food, there is a need of more pronation. Finally, the beginning of feeding is defined as the time of loading the food and the end as the time of unloading the food into mouth. Again there is no comparison data for feeding with a spoon.

Overall, the following aspects can be mentioned about elbow joint rotation. First, except for forearm pronation the range and arc for feeding with a fork and a spoon are almost the same. Second, drinking requires larger flexion arc and smaller pronation-supination while eating requires smaller flexion arc and larger pronation-supination. Third, the large amount of flexion and supination-pronation as a whole for feeding shows the high importance of these two joint rotations. Overall, the required range and arc for these three tasks are:

Elbow:

	Min.	Max.	Arc
- Flexion	70	130	60
- Pronation		40	100
- Supination		60	

For the wrist joint, there are two papers that provide comparison data. As mentioned for wrist extension the data in Table 4.1 is used. In the case of drinking the extension arcs agree (13°), but the range is different (3° - 16.4° versus 11.2° - 24°). The reason again is due to the definition of standard position (zero degrees extension). The first paper (column 2) defines the zero degrees as "the point at which these three [the lateral epicondyle, radial styloid, and center of the second metacarpal head] were linearly aligned while the forearm was held in maximum supination" [Brumfield, et al. 1984, 5]. The second paper did not provide any definition for the standard position. The difference in definition caused the range shift of approximately 8°.

For eating with a fork, the data in this study show a smaller arc (14° versus 27°), while the extension range is within the range of column 4 (14° - 28° versus 9° - 36°). For eating with a spoon, the data in Table 4.2 shows close correspondence to the data for eating with a fork (12.8° versus 14.4° for arc and 13.7° - 18.1° versus 28.1° versus 18.1° - 30.9° for range).

If the above-mentioned 8° shift is taken into account, the general range of extension for drinking would be 11° - 24.4° and its centroid would be 18°, which is very close to the data in column 3 (19°). In the case of eating with a fork the range of extension would be 21.7° - 36.1°

and its centroid would be 29°, which is close to the data in column 5 (32°); for the data in column 4, the centroid is 23° which shows a large difference. The small S.D. (4) for the wrist extension data in this study indicates that it is more reliable. Overall, it can be said that for eating 15° degrees of extension arc is sufficient and the data in this study corresponds more to the actual required extension arc than the data in column 4.

For ulnar and radial deviation there is a very small amount of data to compare with. Only one paper (column 3 and 5) gives the rotation centroids for drinking with a cup and eating with a fork (0 and 7 degrees respectively) and, as previously mentioned, it did not define the neutral position. The very important point about radial-ulnar deviation is that it is extremely sensitive to the way the neutral position is defined. The reason is that it has a very small arc (about 8°). As seen in the last column of Table 4.1, the initial deviation is -2.8°. This initial deviation depends basically on the position of point M on the line connecting markers 5 and 6 on the subject's wrist. Point M was defined as a point which divides 56 in a ratio of 1 to 2 for all ten subjects (in the program ANGROT.FOR). But because the subjects' wrist sizes were different, the point M should have been measured according to a criterion for each individual subject. This method would change the initial deviation and overall it would provide more reliable data.

Overall, the following points can be said about wrist extension and radial-ulnar deviation for all the three tasks. First, for all three tasks the extension and radial-ulnar deviation arc are almost the same (13.5° and 8° respectively). Second, the range of extension and radial-ulnar deviation for the two eating tasks are almost the same and there is a clear distinction between eating and drinking tasks. Third, because radial-ulnar deviation has a smaller arc and range than wrist extension, it can be concluded that wrist extension has a higher importance and priority than wrist radial-ulnar deviation and furthermore, ulnar deviation is more important than radial deviation.

As a whole the required minimum, maximum, and arc for all the three tasks are:

<u>Wrist</u>:

	Min.	Max.	Arc
- Extension:	0	-35	35
- Ulnar Dev.:		15	20
- Radial Dev.:		-5	

These arcs and ranges are generally in agreement with the available published data [Brumfield, 1984, 5; Palmer et al. 1985, 6]. Another important conclusion that can be made based on what was discussed above is that it is possible to determine versatile positions for these two rotations and thus fix the prosthetic wrist at these positions. These positions can be the centroid for each rotation. Thus, 15° extension and 10° ulnar deviation are recommended. Brumfield [Ibid] suggested that "10° of extension is probably the most versatile position for wrist fusion".

In Table 4.2 there is a third wrist rotation ψ. According to the kinematic model that was explained in Chapter 3, three degrees of rotational freedom were chosen for the wrist joint. The physical meaning of this third rotation in clinical terms is inward-outward wrist rotation. For the three feeding tasks the range and the arc of inward-outward rotation are very close (-.4° to 2.1° and 2.5° respectively). These data show that: (1) There is a third wrist rotation as was shown before [Palmer et al. 1984, 6]; (2) It is within the range that was estimated for 52 standardized tasks, i.e., 2.2° to 11.8° [Ibid]; (3) It is very small and thus negligible.

4.3 STICK DIAGRAMS AND ANGLE-TIME GRAPHS

In order to provide a visual presentation of the arm motion pattern, three stick diagrams are given for each task. These three diagrams show the arm motion pattern in three orthogonal planes: top view, side view, and front view. These stick diagrams show the following important aspects of the arm motion. First, it provides the general pattern of the arm motion for each especific task; thus by comparing the stick diagrams of different activities, it is possible to recognize visually the difference in motion patterns (e.g., eating with a fork compared to drinking). Second, from a kinematic point of view it clearly shows the change of velocity and thus acceleration of the arm. Third, it clearly shows the trunk forward motion (body front flexion) and partially shoulder elevation-depression. This helps in understanding the compensation effect of the subject's trunk forward motion on the arm joint rotations during different tasks.

Figures 4.4 to 4.6 show stick diagrams for the three feeding tasks

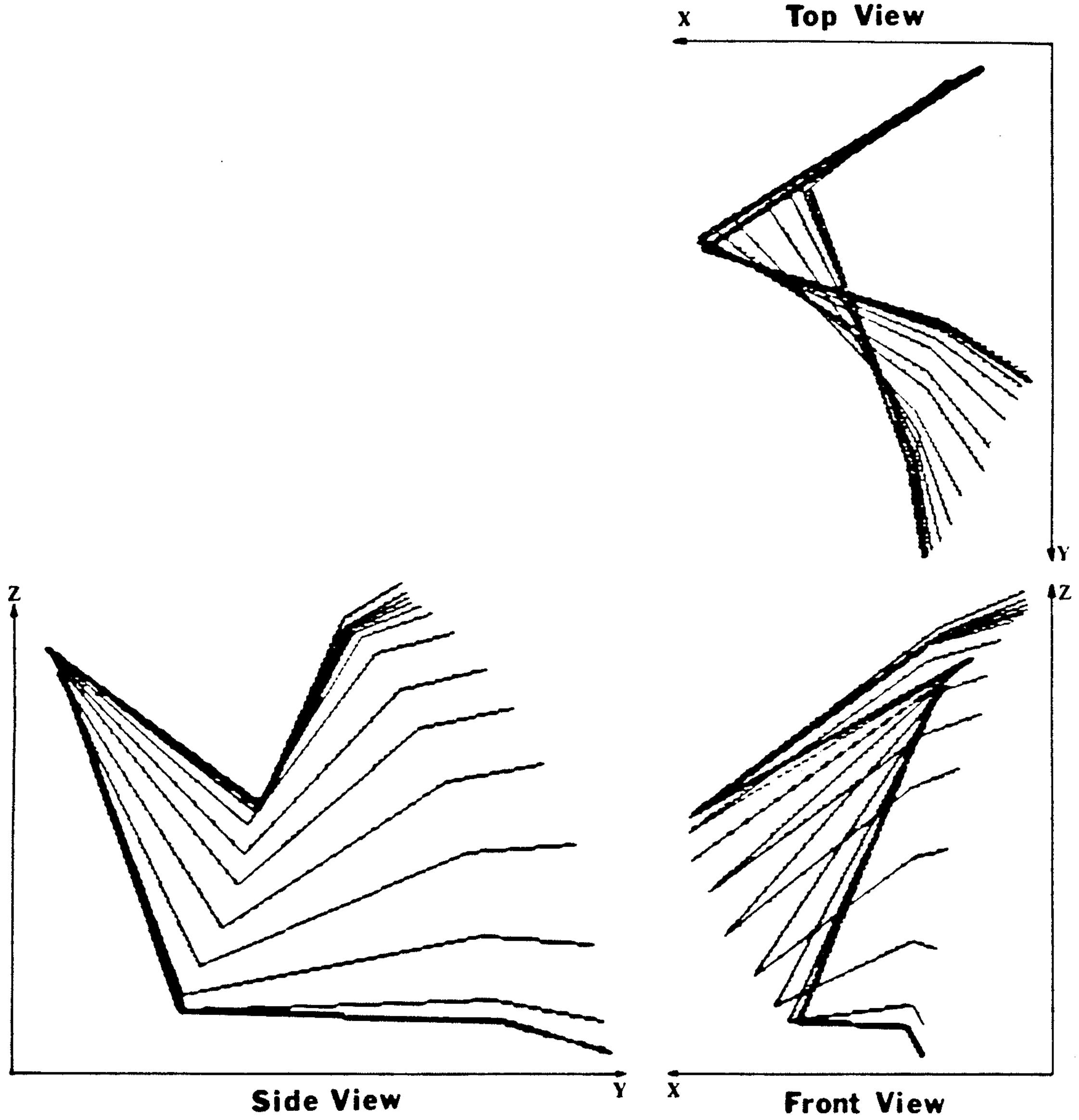


Fig.4.4 STICK DIAGRAM-DRINKING (CUP) WITHOUT BODY MOVEMENT.

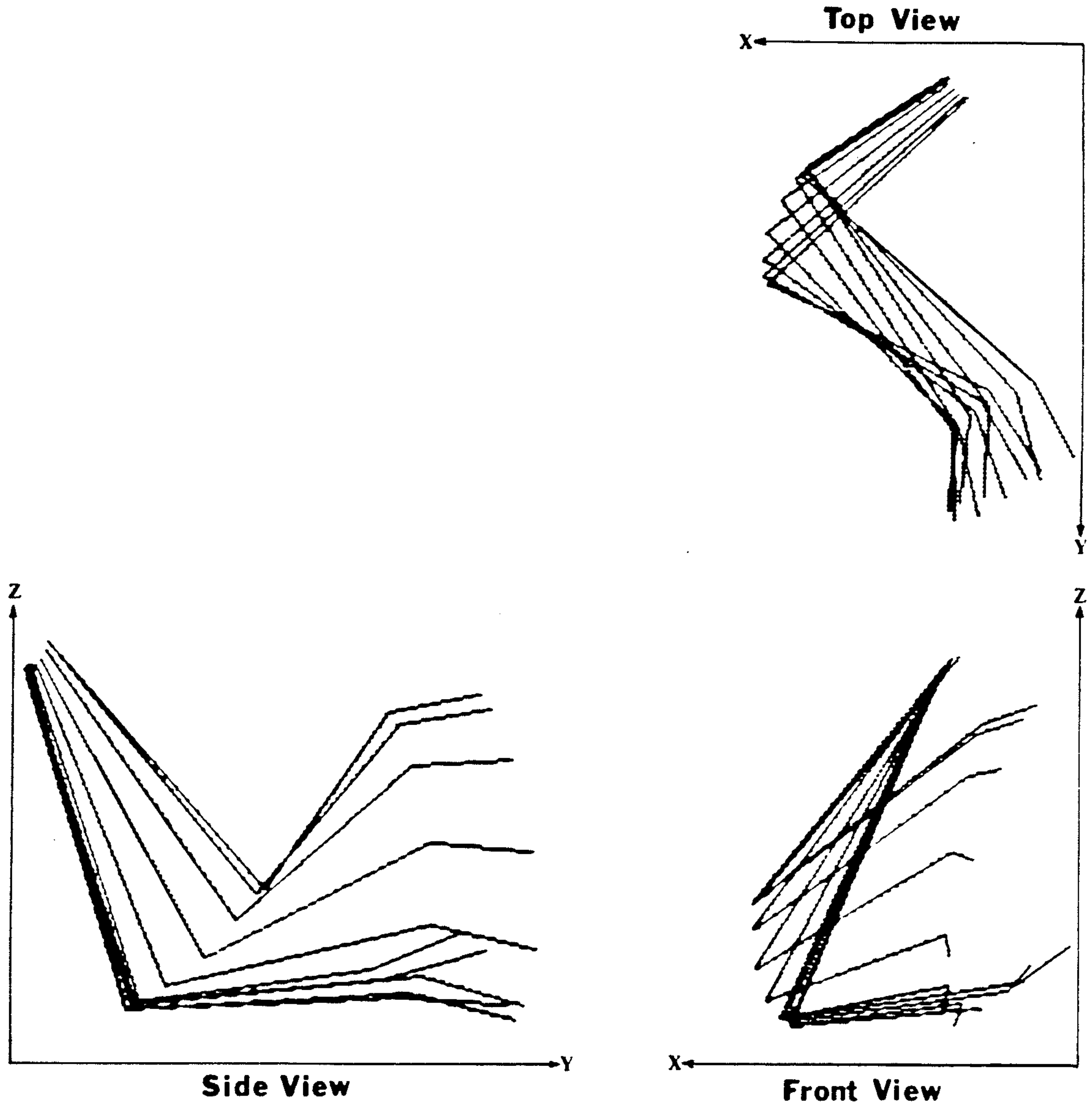


Fig.4.5. STICK DIAGRAM-EATING (FORK) WITHOUT BODY MOVEMENT.

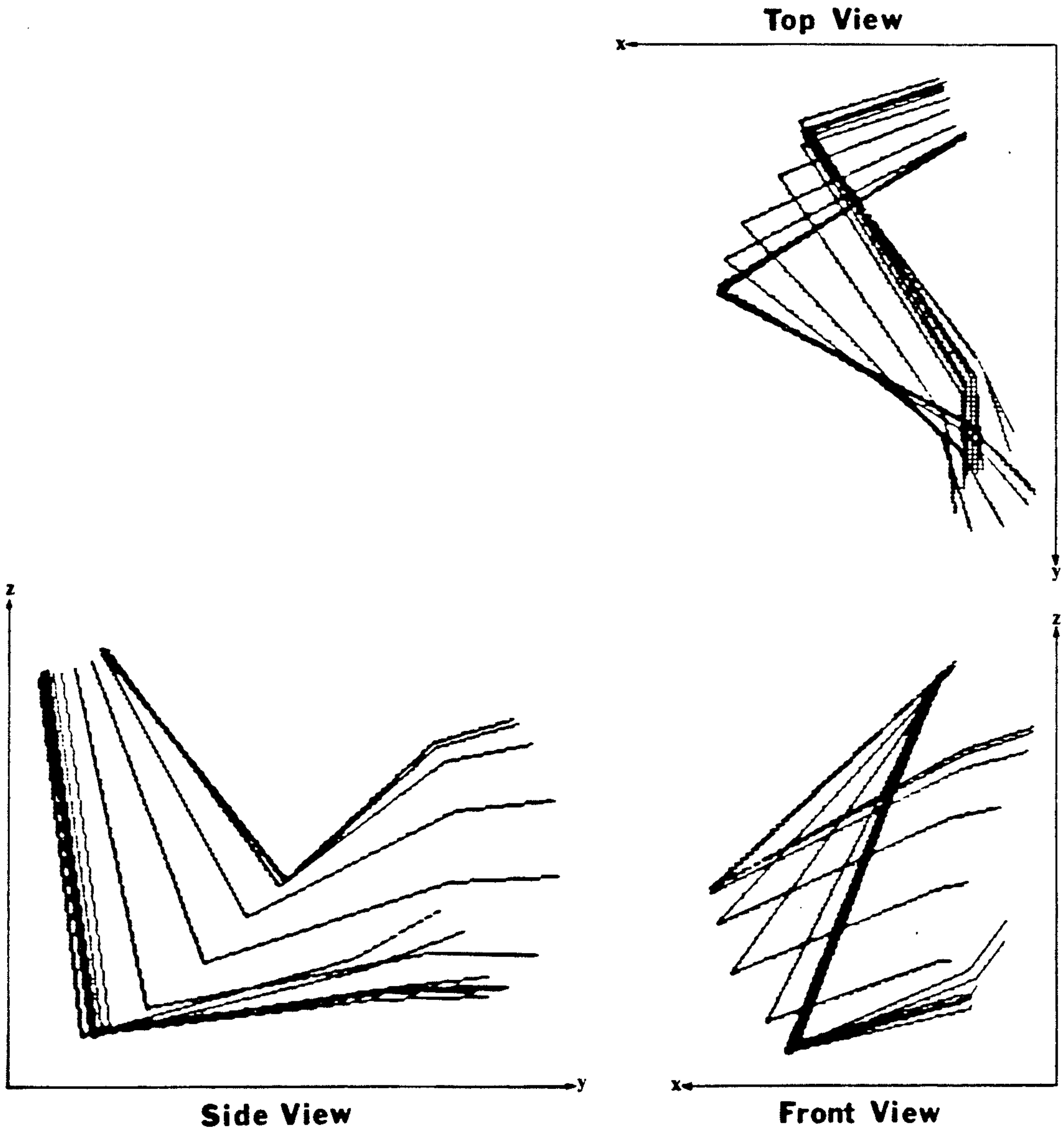


Fig.4.6. STICK DIAGRAM-EATING (SPOON) WITHOUT BODY MOVEMENT.

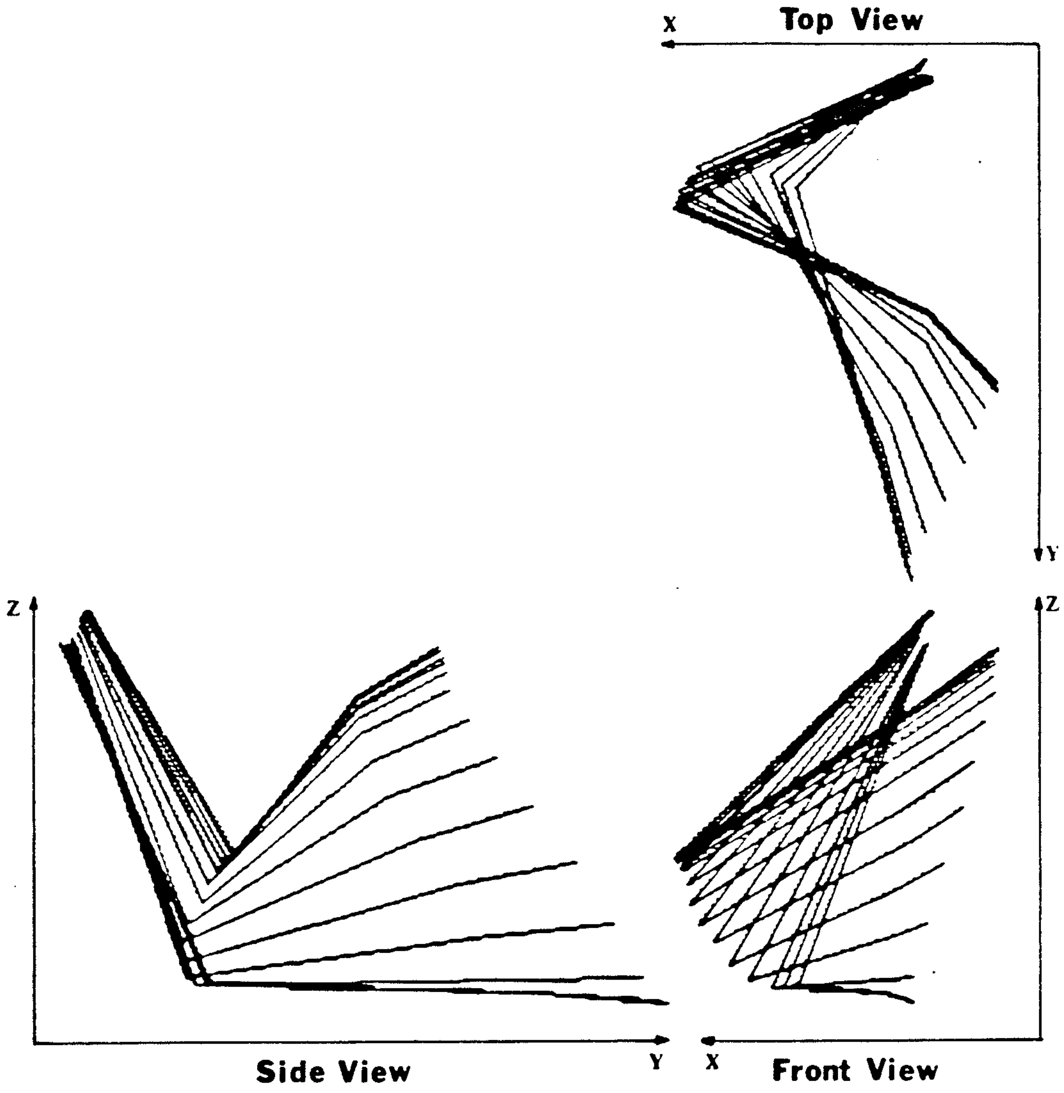


Fig.4.7. STICK DIAGRAM-DRINKING (CUP) WITH BODY MOVEMENT.

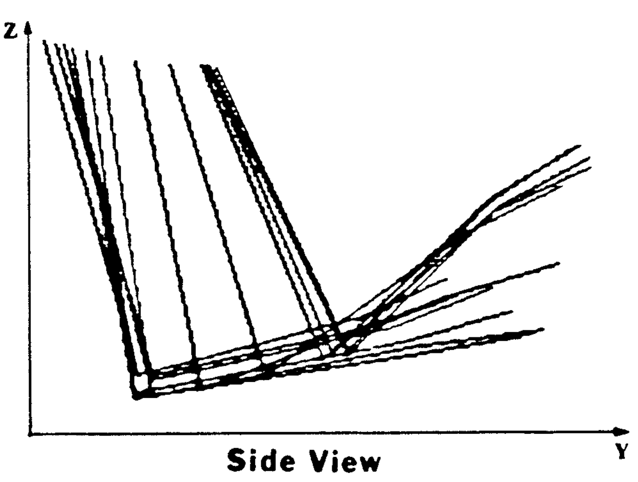


Fig.4.8. STICK DIAGRAM-EATING (FORK) WITH BODY MOVEMENT.

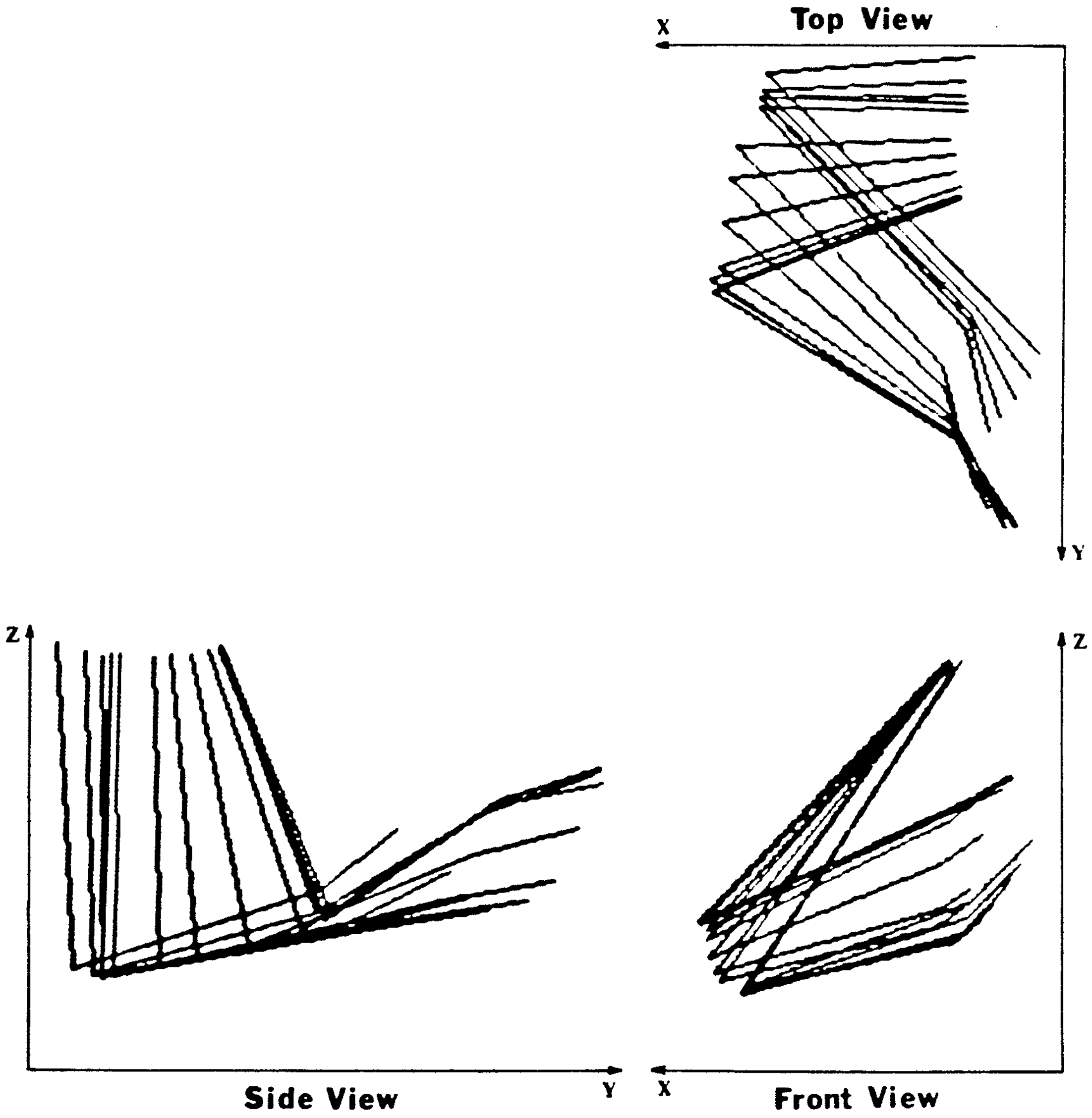


Fig.4.9. STICK DIAGRAM-EATING (SPOON) WITH BODY MOVEMENT.

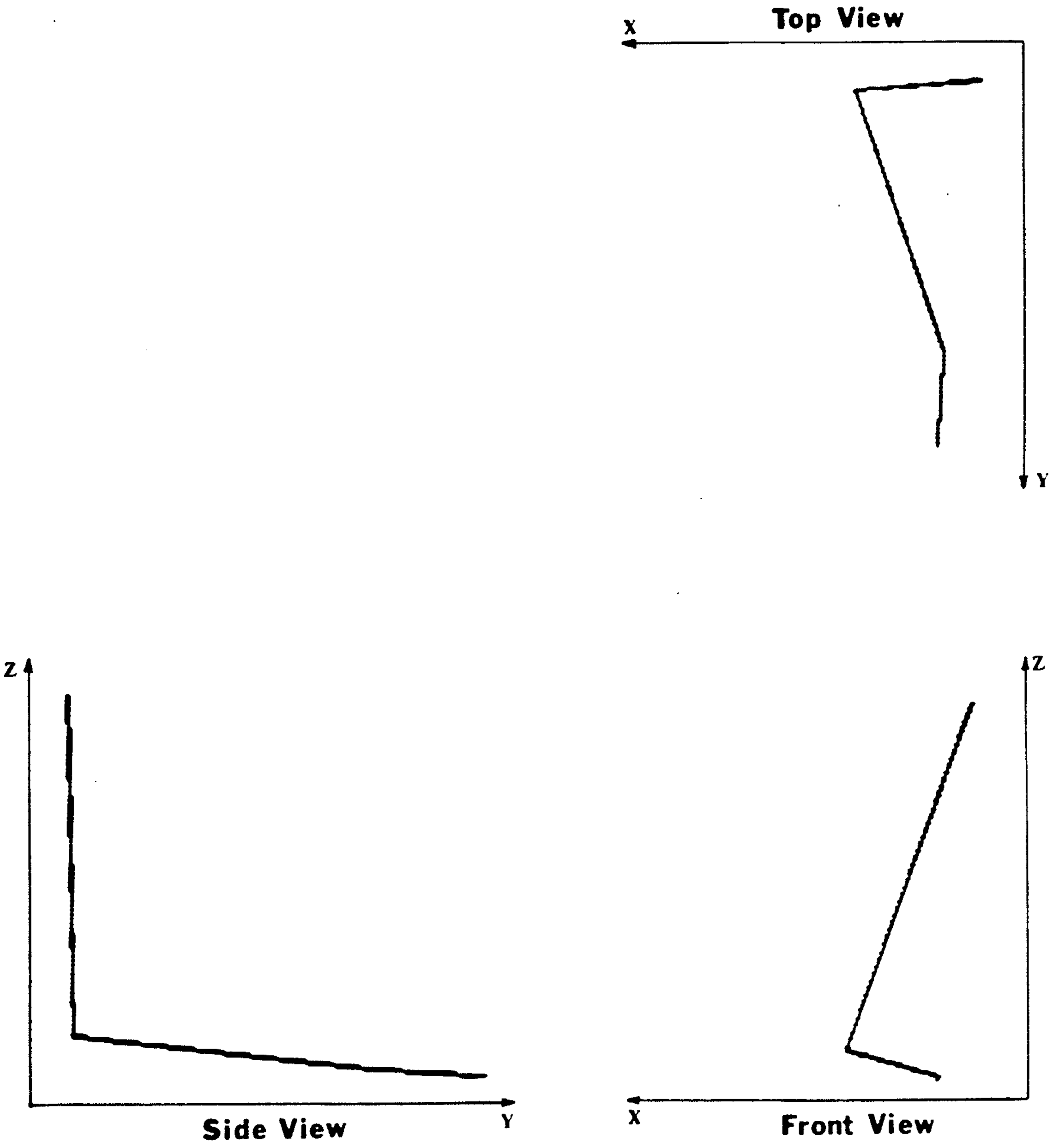


Fig.4.10. STICK DIAGRAM-STANDARD POSITION.

when the subject sits upright. Figures 4.7 to 4.9 show the same tasks while the subject moves his trunk forward. Fig. 4.10 shows the standard position for one of the subjects. It clearly shows some of the initial deviation for the joints.

Angle-time graphs are another way of presenting arm motion patterns. Here, the quantitative changes of different arm joint rotations are presented. These graphs show the individual changes of joint rotations with respect to time. The significance of these graphs is as follows: (1) it provides a visual but quantitative presentation of individual joint rotations, (2) it provides the simultaneous pattern of quantitative changes in different joint rotations during performing different tasks, and (3) it provides the range and arc of each joint rotation visually. Figures 4.11 to 4.19 show the angle-time graphs of the three arm joints for the three feeding tasks. It is noted that these graphs are not smoothed or filtered in any way.

4.4 STATIC AND DYNAMIC ERROR ANALYSIS

One important aspect of any measurement system that should be evaluated is the system measurement error. In the case of the 3-D measurement system, this includes both static and dynamic system errors.

One way of estimating the static error of the system is to calculate the 3-D coordinates of a few reflective spheres whose positions are measured and known. Five white table-tennis balls were used in this method. Their positions were measured with a tape-measure with 1 mm accuracy. The measured and calculated values are tabulated in

FIG.4.11 ANGLE-TIME GRAPH

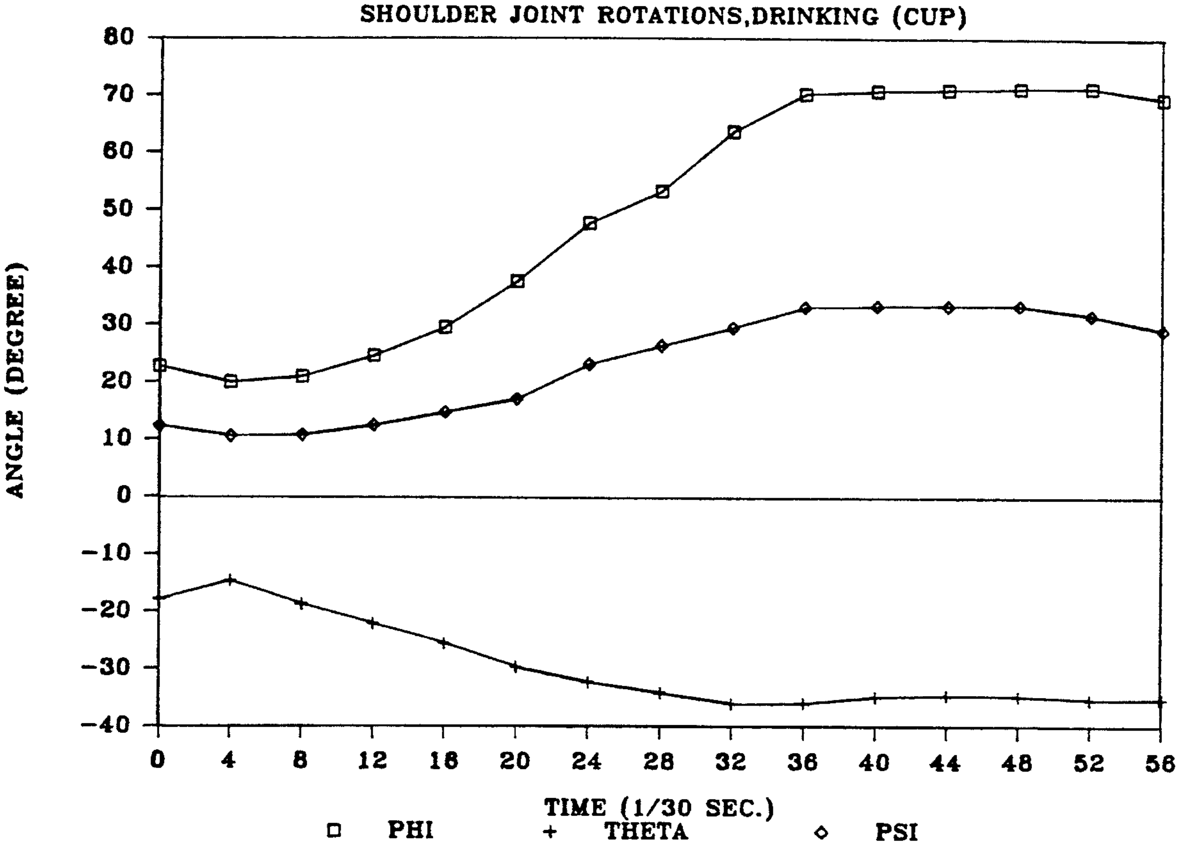


FIG.4.12 ANGLE-TIME GRAPH

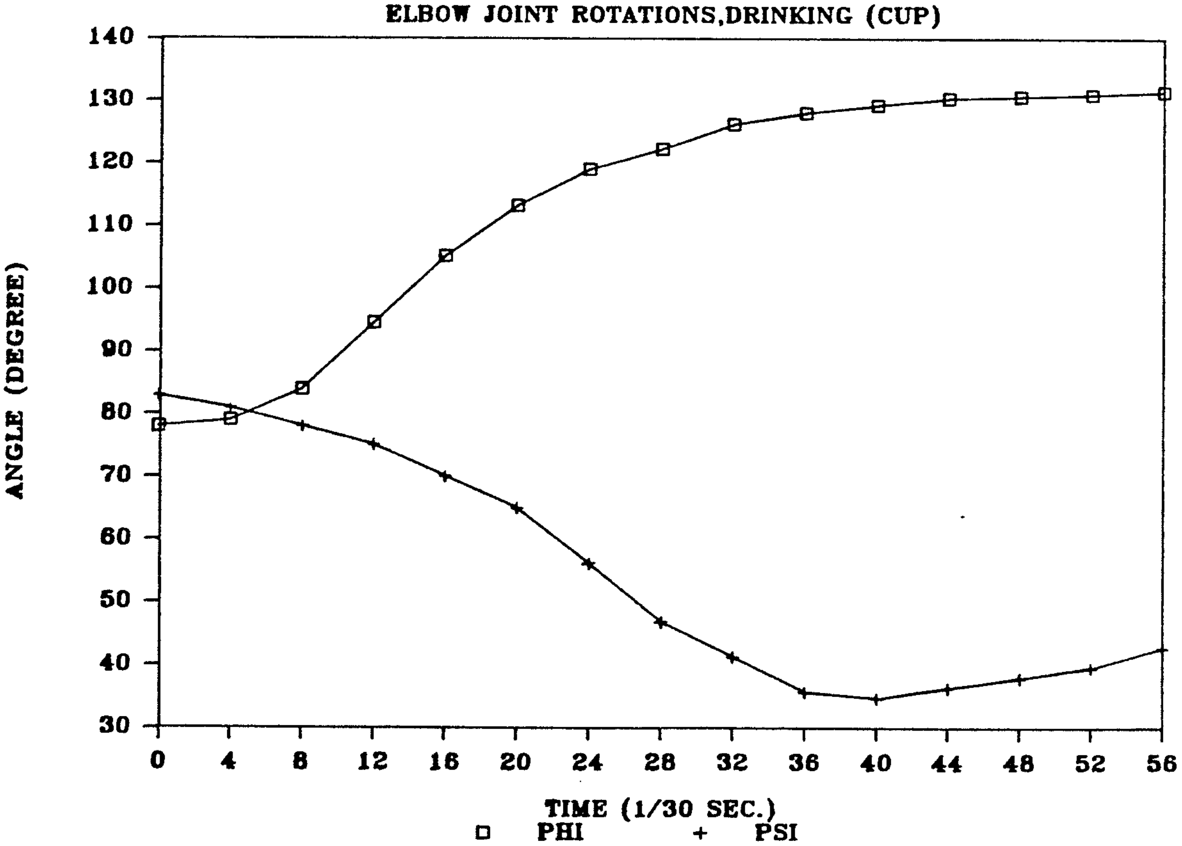


FIG.4.13 ANGLE-TIME GRAPH

WRIST JOINT ROTATIONS,DRINKING (CUP)

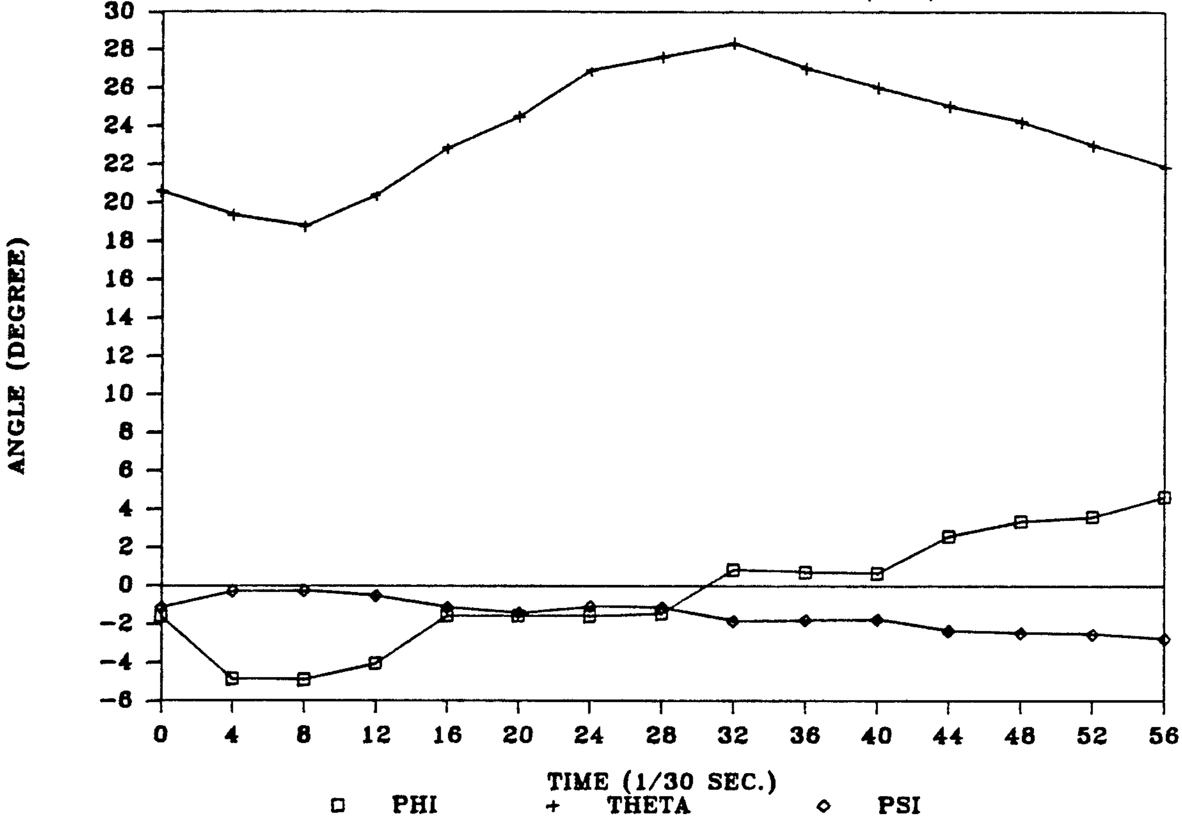


FIG.4.14 ANGLE-TIME GRAPH

SHOULDER JOINT ROTATIONS,EATING (FORK)

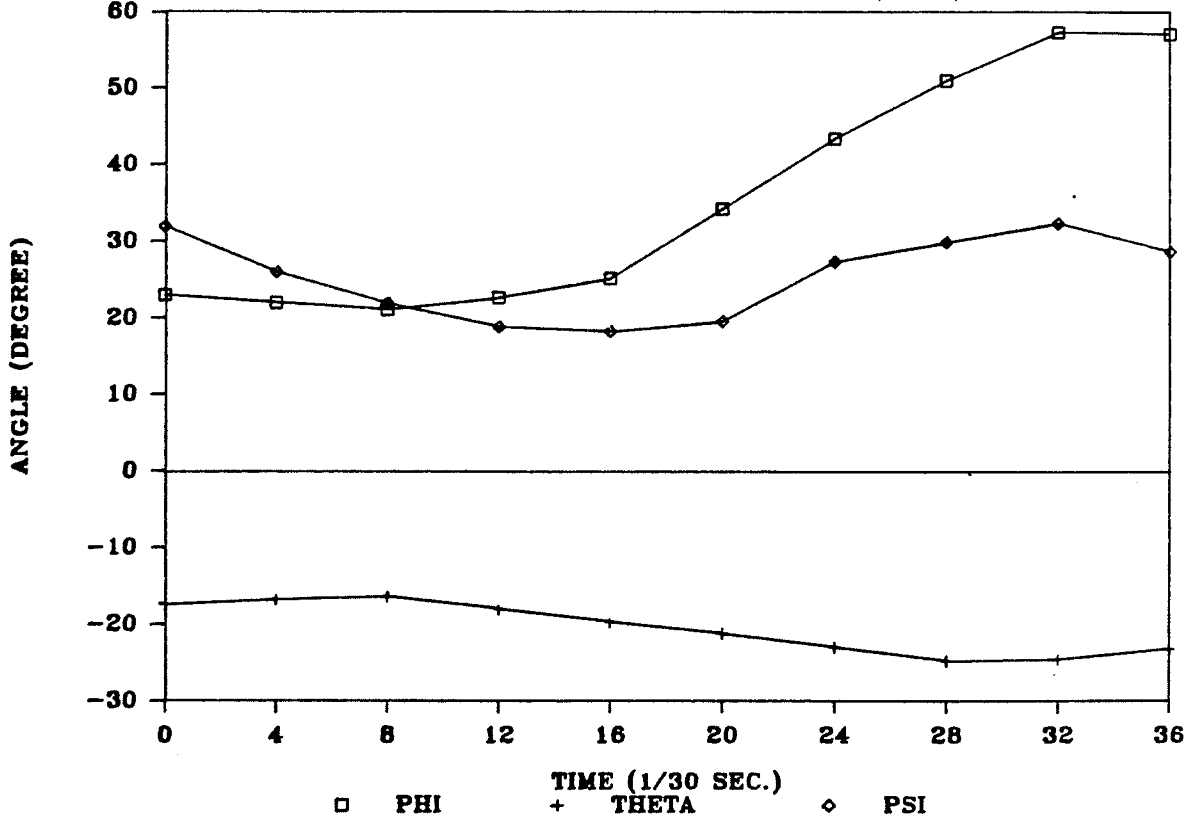


FIG.4.15 ANGLE−TIME GRAPH

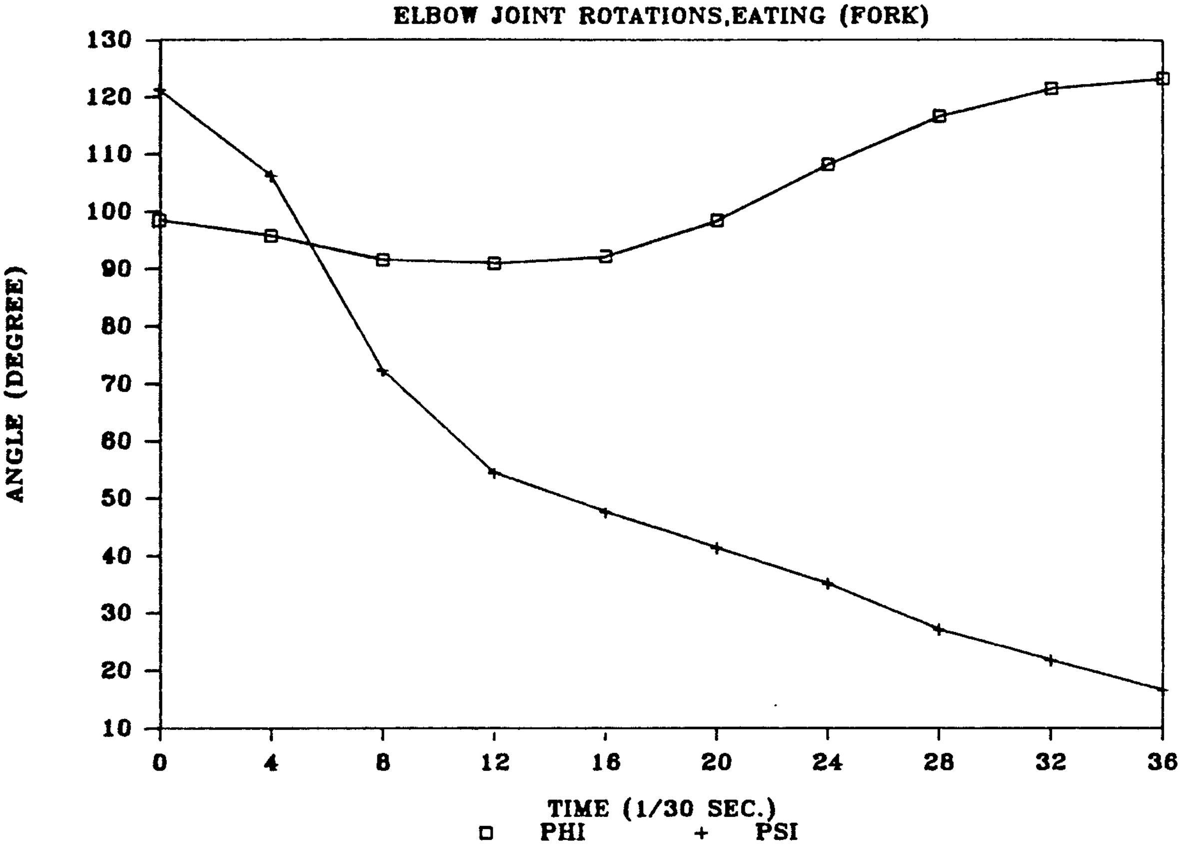


FIG.4.16 ANGLE−TIME GRAPH

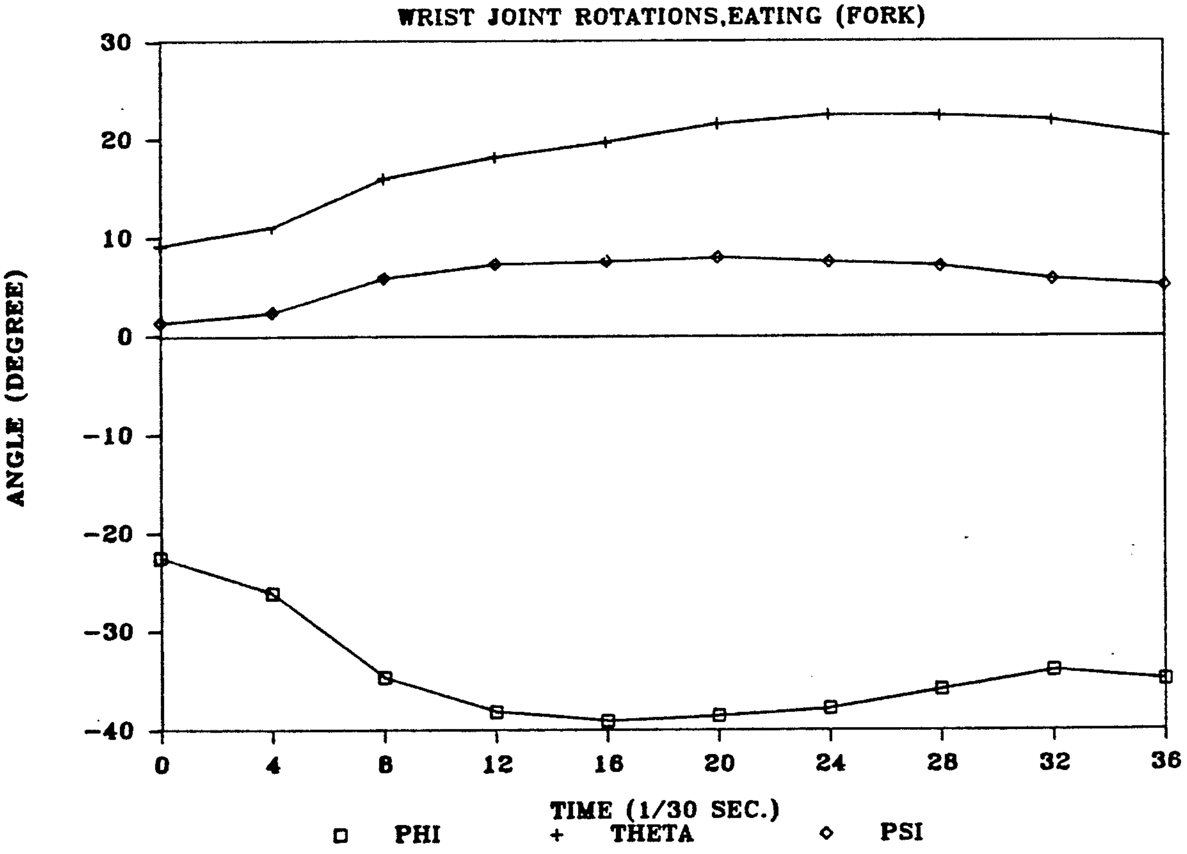


FIG.4.17 ANGLE–TIME GRAPH

SHOULDER JOINT ROTATIONS,EATING (SPOON)

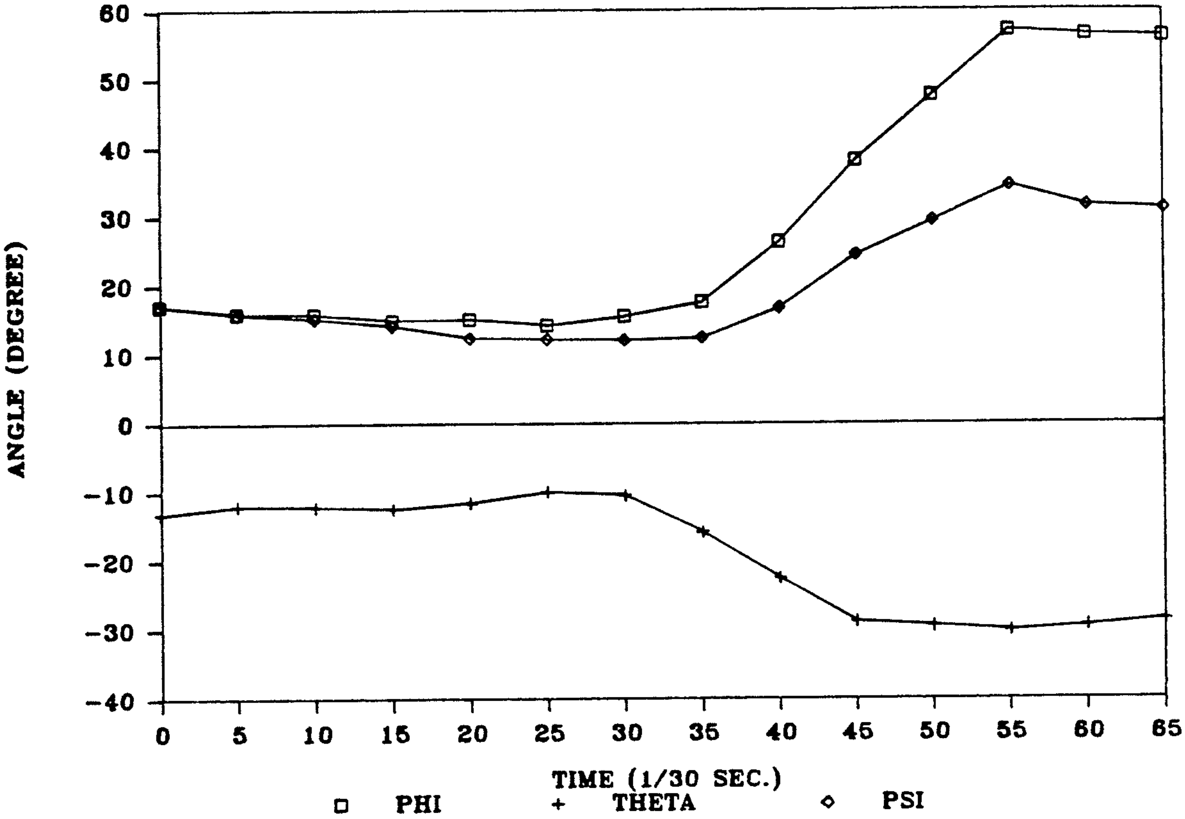


FIG.4.18 ANGLE–TIME GRAPH

ELBOW JOINT ROTATIONS,EATING (SPOON)

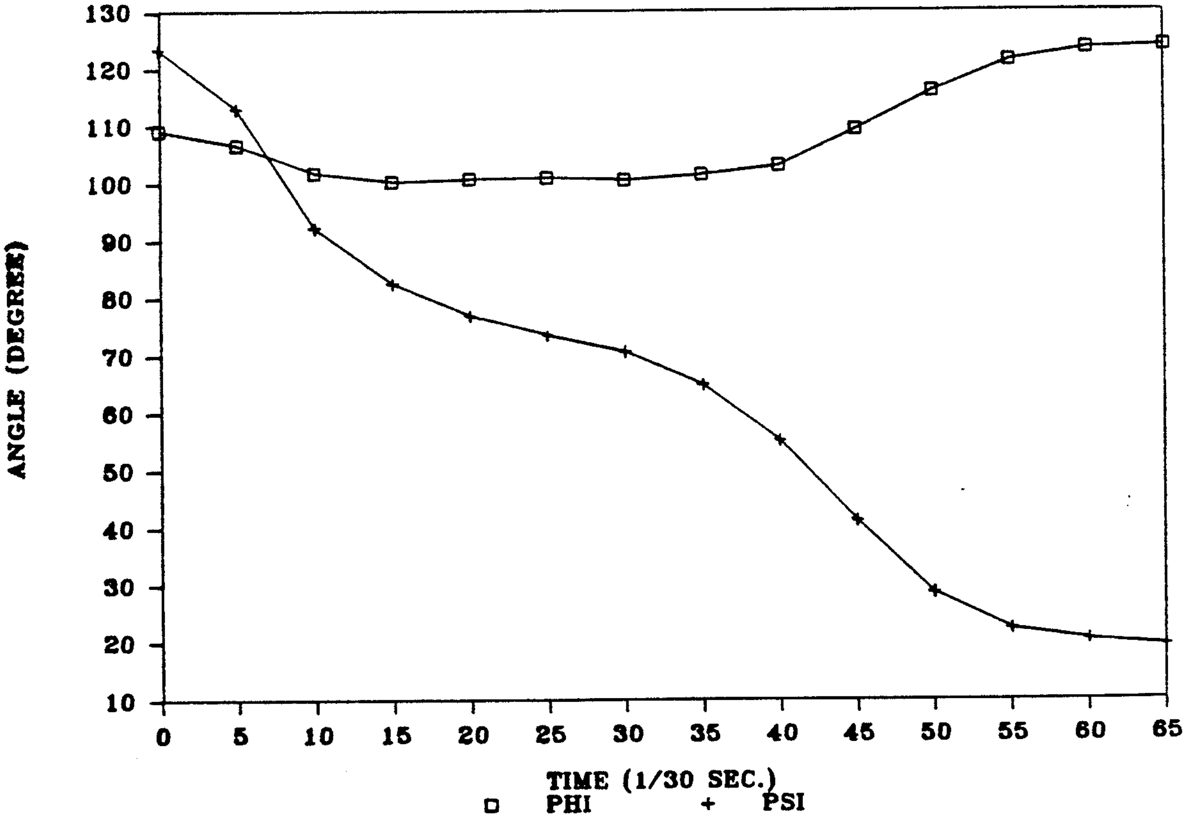
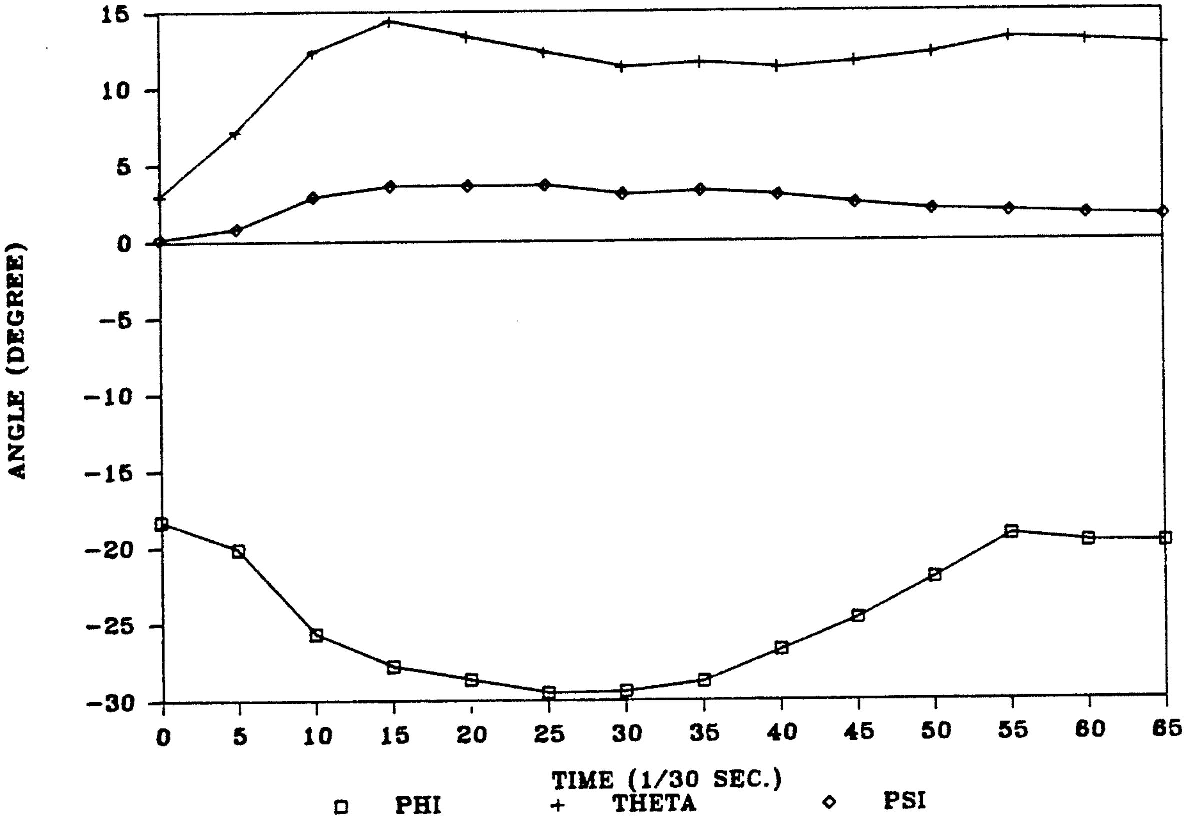


FIG.4.19 ANGLE–TIME GRAPH



WRIST JOINT ROTATIONS,EATING (SPOON)

Table 4.5. The maximum difference is for the Z-coordinate of the fifth ball (7 mm). The field of view was 80 x 80 cm^2 and based on that, the maximum and minimum percentage of errors were calculated to be: +.875% and -.500%. The different factors that were involved in generating this amount of error are:

- the inaccuracy of system calibration;
- the shadows that are around the balls because of non-optimal illumination;
- the noise in the image processing system;
- the error in the measurement of the table-tennis ball coordinates with the tape-measure.

Another method used to estimate the static error of the system was as follows. Markers number 5 and 6 on the subject's arm had a fixed distance w.r.t. each other. This fixed distance was measured (11 cm) and the recorded images of the subject's standard position was processed several times (usually five times). The standard position was a fixed and stationary position and thus the calculated error can be called static error. Based on the processed image, the distance 56 was calculated and compared to the measured value. The minimum and maximum percentages of errors were calculated. This method was applied to all the ten subjects and the results are tabulated in Table 4.6. As can be seen, the mean value of the maximum percentage of error for ten subjects is 1.53% (with a small S.D. .34). This is greater than what was calculated previously (1.53% versus .88%).

The main reason for this discrepancy is the marker sizes. In the former case, table-tennis balls were used which are 1.5 inches in diameter, but in the latter case the reflective markers were used which

TABLE 4.5. STATIC ERROR OF THE SYSTEM (CALIBRATION MARKERS).

TEST MARKER NO.	MEASURED X	 Y	 Z	CALCULATED X	 Y	 Z	DIFFERENCE DEL(X)	 DEL(Y)	 DEL(Z)
1	511	639	319	515	641	320	-4	-2	-1
2	217	1124	269	219	1122	270	-2	+2	-1
3	651	1233	201	654	1232	201	-3	+1	0
4	511	639	138	512	638	137	-1	+1	+1
5	850	879	71	847	878	78	+3	+1	-7

NOTES: ALL DATA ARE IN MM.
FIELD OF VIEW : 800 X 800 SQUARE MM.

TABLE 4.6. STATIC ERROR OF THE SYSTEM
(BODY MARKERS)

SUBJECT	MIN. (%)	MAX. (%)
1	0.85	1.38
2	0.94	1.76
3	0.90	1.66
4	1.02	2.33
5	0.65	1.17
6	1.46	1.72
7	1.05	1.33
8	0.74	1.15
9	1.36	1.56
10	0.64	1.25
MEAN	0.96	1.53
S.D.	0.26	0.34

are 11/16 inch in diameter. Basically, the same sources of error can be mentioned for this method. Another interesting aspect that can be seen in Table 4.6 is the change of percentage of error from a minimum amount (.96%) to a maximum amount (1.53%). These are based on processing the same image five times. This shows clearly the effect of noise in the image processing system. In another words, the acquired image of the markers changes slightly each time that the incoming stationary camera image is captured in the frame buffer, and thus the centroids of the markers change.

The effect of the above-mentioned error of the image processing system on the calculated Euler angles is shown in Table 4.7. The tabulated data are the differences between the maximum and minimum calculated angles (based on processing the original image five times). As can be seen, the effect varies from .14° to 2.75°. Generally, the effect on shoulder joint rotations is much bigger than the other joint rotations. The reason is due to the fact that markers 1, 2, and 3 which define the shoulder body axis, are very close to each other and thus small changes in the centroid coordinates of these markers cause relatively large changes in the direction cosines of the body axes and thus the shoulder joint rotations (which are defined as the relative rotations of the upper arm body axis with respect to shoulder body axis) go through relatively larger changes.

One simple method for the estimation of the system's dynamic error is as follows: As it was explained before, markers number 5 and 6 have a fixed distance with respect to each other. So it is possible to calculate the distance 56 when the subject's arm is in motion and

TABLE 4.7. SYSTEM STATIC ERROR EFFECT ON EULER ANGLES (DEGREES).
(BASED ON STANDARD POSITION DATA)
¦MAX.-MIN.¦ OF EULER ANGLES

JOINT-->	SHOULDER			ELBOW			WRIST		
SUBJECT	PHI	THETA	PSI	PHI	THETA	PSI	PHI	THETA	PSI
1	2.17	1.8	3.05	0.39	-	0.67	1.38	1.24	0.17
2	0.36	2.07	2.22	0.19	-	0.63	0.28	0.29	0.04
3	0.45	2.13	2.33	0.28	-	1.67	0.75	0.23	0.10
4	0.46	3.60	3.63	0.18	-	0.73	0.58	0.61	0.14
5	1.04	1.10	2.80	0.25	-	0.75	0.81	0.28	0.04
6	1.22	2.91	2.10	0.35	-	0.88	0.83	0.37	0.18
7	1.84	1.76	2.99	0.25	-	0.80	3.08	0.80	0.21
8	0.73	0.78	1.42	0.27	-	1.06	0.55	0.33	0.09
9	0.77	1.41	4.49	0.47	-	1.18	0.50	0.58	0.25
10	1.53	3.36	2.51	0.26	-	1.32	0.46	0.12	0.16
MEAN	1.06	2.09	2.75	0.29	-	0.97	0.92	0.48	0.14
S.D.	0.59	0.89	0.82	0.08	-	0.32	0.77	0.32	0.07

estimate the amount of error. This was done for ten subjects for all the three feeding tasks. The results are tabulated in Table 4.8. The overall mean dynamic error for all ten subjects and all three feeding tasks is between +2.65% and -.85% (with S.D. of .99 and 1.29 respectively). Now an important question that can be asked is: Why does error increase in the dynamic situation compared to the static situation (.96% to 1.53% with S.D. .26 and .34 respectively - Table 4.6)? There are two main factors. The first one is the low number of frames per second compared to arm motion speed, especially in the middle of feeding performance (because of maximum arm speed at and around that time). The effect of this condition is the elongation of marker shape and thus a small change of the marker centroid coordinates. The second factor is the shadow around the marker and its change corresponding to the change of marker position in space with respect to the illumination direction. In brief, it is because of non-optimal illumination. The combination of these two factors causes the increase in system error.

Overall this amount of error is acceptable for the functional arm motion study. To improve the accuracy of the system the following provisions should be made.

- More accurate measurement of calibration markers coordinates and thus more accurate estimation of calibration parameters.
- Better illumination in order to minimize shadows around the markers at any position in space.
- Bigger reflective markers.

TABLE 4.8. DYNAMIC ERROR OF THE SYSYTEM.

ACTIVITY -->	DRINKING	(CUP)	EATING	(FORK)	EATING	(SPOON)	ALL	THREE
SUBJECT	%		%		%			%
1	-0.74	3.02	0.0	4.06	0.0	2.10		
2	-1.02	1.45	-0.02	3.44	0.0	4.27		
3	-0.17	2.94	0.0	3.51	0.0	3.78		
4	-6.69	1.41	-1.26	1.67	0.0	3.50		
5	-1.40	2.59	-2.34	1.81	0.0	2.25		
6	-2.66	1.40	0.0	3.76	-0.77	1.02		
7	-0.53	2.17	-0.36	4.20	-0.88	1.98		
8	-1.19	3.20	-0.82	2.90	-1.23	1.55		
9	-0.61	3.48	0.0	2.85	-0.70	0.87		
10	-1.48	2.56	0.0	3.91	-0.71	1.82		
MEAN	-1.65	2.42	-0.48	3.21	-0.43	2.31	-0.85	2.65
S.D.	1.80	0.74	0.75	0.85	0.45	1.10	1.29	0.99

4.5 CONCLUSION

The application of the 3-D measurement system to the functional arm motion has shown the following points:

1- The applicability of the system for this kind of study.

2- Sufficient accuracy (i.e., less than 3% dynamic error) and repeatability of the 3-D measurement system.

3- The system is easy to use and comparatively fast (processing the recorded images of a feeding task typically takes one hour). The required time to make the subject ready and do the experiment is less than 10 minutes. If the syncing problem between the VCR and PC-image acquisation system is solved, the total required time to process the recorded images for each task with sufficient sampling frequency would be less than 30 minutes.

The analysis of the collected data from ten subjects performing three feeding tasks has shown the following points.

1- Overall, the collected data shows the correct required range and arc for the three tasks.

2- The kinematic model for the three arm joints is valid and provides correct arm joint rotation patterns.

3- The overall required range and arc for three feeding tasks can be summarized as shown in Table 4.9.

TABLE 4.9 The Required Range and Arc for Feeding

JOINT(ROTATIONS)	RANGE		ARC
	Min.	Max.	
SHOULDER			
- Flexion	5	45	40
- Abduction	-5	-30	25
- In. Rotation	5	25	20
ELBOW			
- Flextion	70	130	60
- Pronation		40	}100
- Supination		60	
WRIST			
- Extension	0	-35	35
- Ulnar Deviation		15	}20
- Radial Deviation		-5	

4- The relative importance of different arm joint rotations for feeding tasks is as follows: elbow flexion, elbow supination, elbow pronation, three shoulder rotations, wrist extension, wrist ulnar deviation and finally wrist radial deviation. This is in general agreement with the study at UCLA (Table 2.2) [Keller et al. 1947, 9; Mason, 1977, 10]. However, it also shows that for feeding tasks elbow supination, wrist extension, and wrist ulnar deviation have a much higher relative importance than the UCLA report concluded (for 51 ADL).

5- It can be said that the two wrist rotations can be eliminated and fixed versatile positions can be used instead (15° wrist extension and 10° ulnar deviation). Also, the extreme importance of forearm supination-pronation should be emphasized as was done by Stein at the University of Alberta [Stein et al. 1980, 11]. All the three shoulder rotations are almost at the same level of importance for feeding tasks. A fixed versatile axis of rotation for shoulder (for feeding tasks) is a logical alternative as was addressed by Enger [Enger, 1967, 12].

6- As a whole it can be concluded that the most crucial rotations that should be provided for a prosthetic arm are elbow flexion and forearm supination-pronation.

CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

An approach to the design of a prosthetic arm controller is formulated. This approach is based on a fundamental study of functional human arm motion. To provide a proper basis and direction for this type of study, human arm movements were classified. To study different aspects of the approach, a new 3-D measurement system was developed.

The 3-D measurement system was applied to study three feeding tasks: drinking with a cup, eating with a fork, and eating with a spoon. Ten right-handed healthy males participated in the experiment. Food with different degrees of consistency were used. It was concluded that for the three feeding tasks, the required range of rotations were: for the shoulder 5 to 45 degrees flexion, 5 to 30 degrees abduction, and 5 to 25 degrees inward rotation; for the elbow 70 to 130 degrees flexion, 40 degrees pronation, and 60 degrees supination; for the wrist 0 to 35 degrees extension, 15 degrees ulnar deviation, and 5 degrees radial deviation. It was concluded that elbow flexion and forearm pronation-supination are the most important elementary motions. Also, it was shown that wrist inward-outward rotation was negligible and that versatile fixed positions of 15 degrees of wrist extension and 10 degrees of ulna deviation could be used. The three shoulder rotations were of equal importance.

In order to provide a better understanding of joint rotations and motion patterns, the collected data were presented in two other forms: stick-diagrams and angle-time graphs. Some aspects of functional arm motion patterns can be seen and understood more easily using these two forms.

The maximum static error of the system is 1.53% and the dynamic error is between -.85% to 2.65%. Thus the system has a sufficient static and dynamic accuracy for functional arm motion study.

Overall, the following conclusions can be made:

1. An approach to the design of a prosthetic arm controller is formulated.
2. The fundamental bases for this approach are developed, i.e.,
    - the fundamental questions that should be studied and answered;
    - the classification of human arm motion;
    - the 3-D measurement system (hardware and software);
3. The 3-D measurement system is applicable and has sufficient accuracy for functional arm motion study. Its repeatability is shown by relatively consistent results for ten subjects (smaller S.D. for the min. and max. required rotations compared to the results of other studies). It is easy to use and more suitable for this type of study than any other system that has been used before.
4. The kinematic model for three arm joints is valid and provides correct arm joint rotation patterns.
5. The high importance of elbow flexion and forearm pronation-supination for feeding tasks is shown, and versatile

fixed positions for wrist extension and ulnar deviation are recommended.

6. The compensation effect of body and head forward motion on the range and arc of different joints is shown. This and the existence of S.D. (4 to 19) for the minimum and maximum required rotations (for all joints) provide a relatively flexible condition for preprogramming feeding tasks.

Important problems that should be solved in order to improve the 3-D measurement system and those aspects that should be studied in the future to provide thorough and detailed information for developing new control strategies for prosthetic arm are as follows:

1. The syncing problem between VCR and PC-image acquisition system is the most important problem to be solved. Solving this would drastically reduce the processing time.
2. Accurate definition of standard position and development of a proper technique for checking the defined standard position.
3. Developing a better illumination system in order to minimize shadows around the markers, to minimize the reflection from the subject's skin and consequently putting all the markers directly on the subject's skin (minimizing the displacement of markers 1, 2, and 3 and thus the effect of one source of error).
4. Using bigger reflective markers.
5. Study of other activities of daily life (e.g., selfcare and hygiene, dressing).

6. Study of versatile axis of shoulder rotation for feeding tasks.
7. Study of general pattern of change of forearm supination-pronation with respect to elbow flexion for feeding tasks in order to couple these two rotations.
8. Study of the effects of using fixed versatile positions for two wrist rotations on the other arm joints and subject's body and head movements (the compensation problem).
9. Study of specific implications of the fundamental study of functional human arm motion on the development of control strategies for prosthetic arm in general and EMG-control (Cybernetic control) in particular.

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7. Appendices

A. Complete list of programs

```
      PROGRAM SYSTEM CALIBRATION ONE
$INCLUDE:'FORINTF.H'
$INCLUDE:'SUB3.FOR'
C
C INITIALIZATION
C
      INTEGER*2 X,Y,I,J,K,P,Q,R,M,N1,XCOR(100),YCOR(100),DELX,DELY,
     1          L(576),O,S,T,XP(100),YP(100),DX,U,V,W,ROW,COL,POSN
      REAL*8 X1,X2,DX1,X3(8),Y1,Y2,Y3(8),DELX1,DELY1,X4(8),
     1       Y4(8),Z4(8),E(16,11),D(16,1),F(11,16),SUM,
     1       A(11,11),H(11,11),B(11,16),C(11,1),L1(11),G(11,11)
      DIMENSION INDEX(11,3)
      CHARACTER BUFFER(256)
C
C CREATING A NEW FILE FOR 11 CALIBRATION PARAMETERS
C
      OPEN (5,FILE='CALIB1.TXT',STATUS='NEW')
C
C IMAGE PROCESSING
C
      I=INIT(620)
      CALL AUTO
      CALL CHAN(1)
      CALL QUADM(1)
      CALL DQUAD(0)
   18 CALL SETIND(0)
      CALL CLEAR(0,7)
      CALL SBUF(1)
      WRITE (*,'(A\)') ' CHOOSE THRESHOLD VALUE : '
      READ (*,'(BN,I6)') I
      CALL SCALING(0,255,I,255,BUFFER)
      CALL SCALING(I+1,0,255,0,BUFFER)
      CALL LUTD(0,0,0,256,BUFFER)
      CALL SYNC(1)
      CALL SNAP(1)
      CALL SYNC(0)
      WRITE(*,'(A\)') ' IS THE PROCESSED IMAGE ACCEPTABLE (YES/NO:1/0)?'
      READ(*,'(BN,I6)') J
      IF (J.EQ.1) THEN
          GOTO 17
      ELSE
          GOTO 18
      ENDIF
C
C READING THE IMAGE  I X I  (I: READING INCREAMENT )
C PROCESSING THE IMAGE BY USING THRESHOLD VALUE : 0 / 1
C
  17  WRITE (*,'(A\)') ' CHOOSE READING INCREAMENT : '
      READ (*,'(BN,I6)') M
      OPEN (2,FILE='TEM0.TXT',STATUS='NEW')
      J=1
      DO 5 Y=1,477,M
         DO 10 X=1,511,M
            I=IFIXR(X,Y)
            IF(I.EQ.255)THEN
               XCOR(J)=X
               YCOR(J)=Y
               WRITE (2,*) XCOR(J),YCOR(J)
               J=J+1
            ENDIF
```

```
   10    CONTINUE
    5 CONTINUE
C
C WINDOWING
C DELETION OF PIXELS WITH VALUE EQUAL TO 105
C CALCULATION OF TRANSITION POINTS IN EACH WINDOW
C CALCULATION OF CENTROID OF EACH MARKER :2-D COORDINATES
C
      REWIND 2
      OPEN (3,FILE='TEM1.TXT',STATUS='NEW')
      I1=0
      P=0
      O=1
      WRITE (*,'(A\)') ' CHOOSE WINDOW SIZE : '
      READ (*,'(BN,I6)') N
      DO 20 K=1,J-1
         READ (2,*) XCOR(K),YCOR(K)
         X2=0.0
         Y2=0.0
         DX1=0.0
         DO 40 Y=YCOR(K)-N,YCOR(K)+N
            DO 30 X=XCOR(K)-N,XCOR(K)+N
               I=IPIXR(X,Y)
               L(O)=I
               S=O-1
               IF(S.EQ.0)L(S)=0
               IF(L(O).EQ.105)L(O)=L(S)
               IF(L(O).NE.P)THEN
                  XP(O)=X
                  YP(O)=Y
                  T=O-1
                  IF(L(O).EQ.0)THEN
                     DX=XP(O)-XP(T)
                     X1=(XP(O)-DX/2.)*DX
                     Y1=YP(O)*DX
                     X2=X2+X1
                     Y2=Y2+Y1
                     DX1=DX1+DX
                  ENDIF
                  P=I
                  O=O+1
               ENDIF
   30       CONTINUE
   40    CONTINUE
         IF (DX1.LT.50) GOTO 20
         I1=I1+1
         X3(K)=X2/DX1
         Y3(K)=Y2/DX1
         WRITE (3,*) X3(K),Y3(K)
   20 CONTINUE
      IF (I1.LT.8) THEN
          WRITE (*,'(A\)') 'NUMBER OF DETECTED MARKERS IS LESS THAN 8 '
          GOTO 55
      ENDIF
C
C ELIMINATION OF REPEATED DATA
C
      OPEN (4,FILE='TEM2.TXT',STATUS='NEW')
      REWIND 3
      W=I1
      IF(W.GT.8)THEN
         GOTO 45
      ELSE
         DO 35 K=1,W
            READ (3,*) X3(K),Y3(K)
            WRITE (4,*) X3(K),Y3(K)
```

```
   35     CONTINUE
          GOTO 51
      ENDIF
   45 DO 46 K=1,W
          READ (3,*) X3(K),Y3(K)
   46 CONTINUE
      I2=0
      DO 50 M=1,W
         J=M+1
   60    IF(J.GT.W)GOTO 70
         DELX1=X3(J)-X3(M)
         DELY1=Y3(J)-Y3(M)
         IF(.NOT.((ABS(DELX1).LT.3.0).AND.(ABS(DELY1).LT.3.0)))THEN
            J=J+1
            GOTO 60
         ELSE
            GOTO 50
         ENDIF
   70    WRITE (4,*) X3(M),Y3(M)
         I2=I2+1
   50 CONTINUE
      IF (I2.NE.8) THEN
          WRITE (*,'(A\)') ' NUMBER OF DETECTED MARKERS IS NOT EQUAL TO
     18 '
          GOTO 55
      ENDIF
C
C READING THREE DIMENTIONAL COORDINATES OF CONTROL POINTS FROM SCREEN:
C X4(K),Y4(K),Z4(K)  ACCORDING TO THE ORDER OF MARKERS IN THE TWO
C DIMENTIONAL IMAGE
C
   51 WRITE (*,'(A\)') ' ATTENTION : ALL THE INPUT DATA SHOULD BE IN MET
     1ERS WITH THREE DECIMAL POINTS'
      DO 100 K=1,8
         WRITE (*,*) K
         WRITE(*,'(A\)') '                 X4(K)=   '
         READ(*,'(BN,F6.3)') X4(K)
         WRITE (*,*) K
         WRITE(*,'(A\)') '                 Y4(K)=   '
         READ(*,'(BN,F6.3)') Y4(K)
         WRITE (*,*) K
         WRITE(*,'(A\)') '                 Z4(K)=   '
         READ(*,'(BN,F6.3)') Z4(K)
  100 CONTINUE
C
C DEFINING THE ELEMENTS OF THE MATRIX [P]:[16 X 11]
C
C                               T
C TRANSPOSE OF MATRIX [P] : [P]  =[R] : [11 X 16]
C
      REWIND 4
      DO 105 I=1,8
          READ (4,*) X3(I),Y3(I)
  105 CONTINUE
      DO 110 I=1,15,2
         J=(I+1)/2
         E(I,1)=X4(J)
         F(1,I)=X4(J)
         E(I,2)=Y4(J)
         F(2,I)=Y4(J)
         E(I,3)=Z4(J)
         F(3,I)=Z4(J)
         E(I,4)=1.0
         F(4,I)=1.0
         E(I,5)=0.0
         F(5,I)=0.0
```

```
            E(I,6)=0.0
            F(6,I)=0.0
            E(I,7)=0.0
            F(7,I)=0.0
            E(I,8)=0.0
            F(8,I)=0.0
            E(I,9)=-X3(J)*X4(J)
            F(9,I)=-X3(J)*X4(J)
            E(I,10)=-X3(J)*Y4(J)
            F(10,I)=-X3(J)*Y4(J)
            E(I,11)=-X3(J)*Z4(J)
            F(11,I)=-X3(J)*Z4(J)
  110  CONTINUE
         DO 120 I=2,16,2
            J=I/2
            E(I,1)=0.0
            F(1,I)=0.0
            E(I,2)=0.0
            F(2,I)=0.0
            E(I,3)=0.0
            F(3,I)=0.0
            E(I,4)=0.0
            F(4,I)=0.0
            E(I,5)=X4(J)
            F(5,I)=X4(J)
            E(I,6)=Y4(J)
            F(6,I)=Y4(J)
            E(I,7)=Z4(J)
            F(7,I)=Z4(J)
            E(I,8)=1.0
            F(8,I)=1.0
            E(I,9)=-Y3(J)*X4(J)
            F(9,I)=-Y3(J)*X4(J)
            E(I,10)=-Y3(J)*Y4(J)
            F(10,I)=-Y3(J)*Y4(J)
            E(I,11)=-Y3(J)*Z4(J)
            F(11,I)=-Y3(J)*Z4(J)
  120  CONTINUE
C
C DEFINING THE ELEMENTS OF THE MATRIX [Q]:[16 X 1]
C
         DO 130 I=1,15,2
            J=(I+1)/2
            D(I,1)=X3(J)
  130  CONTINUE
         DO 140 I=2,16,2
            J=I/2
            D(I,1)=Y3(J)
  140  CONTINUE
C                                 T
C MATRIX MULTIPLICATION : [A]=[P] [P] : [11 X 11]
C
         DO 170 ROW=1,11
            DO 180 COL=1,11
               SUM=0.0
               DO 190 POSN=1,16
                  SUM=SUM+F(ROW,POSN)*E(POSN,COL)
  190          CONTINUE
               A(ROW,COL)=SUM
  180       CONTINUE
  170  CONTINUE
         OPEN (11,FILE='MAT.TXT',STATUS='NEW')
         DO 191 J=1,11
              DO 192 I=1,11
                  WRITE (11,*) A(I,J)
  192         CONTINUE
```

```
  191 CONTINUE
C                           -1
C MATRIX INVERTION : [H]=[A]    : [11 X 11]
C GAUSS-JORDAN METHOD
C
      N=11
      CALL MATINV(A,N)
      DO 221 J=1,11
          DO 222 I=1,11
             H(I,J)=A(I,J)
  222     CONTINUE
  221 CONTINUE
C
C REGENERATING  MATRIX  [A]
C
      REWIND 11
      DO 205 J =1,11
          DO 206 I=1,11
              READ (11,*) A(I,J)
  206     CONTINUE
  205 CONTINUE
C
C CALCULATION OF IDENTITY MATRIX : [I] = [A] [H]
C
      DO 201 ROW=1,11
          DO 202 COL=1,11
              SUM=0.0
              DO 203 POSN=1,11
                  SUM=SUM+A(ROW,POSN)* H(POSN,COL)
  203         CONTINUE
              G(ROW,COL)=SUM
  202     CONTINUE
  201 CONTINUE
      WRITE (*,'(A)') '    MATRIX   [I] : [11 X 11]  '
      DO 208 J=1,11
          DO 209 I=1,11
              WRITE (*,*) G(I,J)
  209     CONTINUE
  208 CONTINUE
C                                      T     -1    T
C MATRIX MULTIPLICATION : [B]=( [P] [P] )   [P]  : [11 X 16]
C
      DO 230 ROW=1,11
          DO 240 COL=1,16
              SUM=0.0
              DO 250 POSN=1,11
                  SUM=SUM+H(ROW,POSN)*F(POSN,COL)
  250         CONTINUE
              B(ROW,COL)=SUM
  240     CONTINUE
  230 CONTINUE
C                                      T     -1    T
C MATRIX MULTIPLICATION : [C]=( [P] [P] )   [P] [Q] : [11 X 1]
C
      DO 260 ROW=1,11
          COL=1
          SUM=0.0
          DO 280 POSN=1,16
              SUM=SUM+B(ROW,POSN)*D(POSN,COL)
  280     CONTINUE
          C(ROW,COL)=SUM
  260 CONTINUE
C
C DEFINING THE ELEMENTS OF THE  CALIBRATION SYSTEM : [L]
C
      DO 281 I=1,11
```

```
          L1(I)=C(I,1)
  281 CONTINUE
C
C STORING CALIBRATION PARAMETERS IN A FILE
C
      WRITE (*,'(A)') '  CALIBRATION PARAMETERS  L1(I) '
      DO 290 I=1,11
          WRITE(5,*)L1(I)
          WRITE(*,*)L1(I)
  290 CONTINUE
   55 CALL PEXIT
      STOP
      END
```

```
      PROGRAM SYSTEM CALIBRATION TWO
$INCLUDE:'FORINTF.H'
$INCLUDE:'SUB3.FOR'
C
C INITIALIZATION
C
      INTEGER*2 X,Y,I,J,K,P,Q,R,M,N1,XCOR(100),YCOR(100),DELX,DELY,
     1          L(576),O,S,T,XP(100),YP(100),DX,U,V,W,ROW,COL,POSN
      REAL*8 X1,X2,DX1,X3(8),Y1,Y2,Y3(8),DELX1,DELY1,X4(8),
     1       Y4(8),Z4(8),E(16,11),D(16,1),F(11,16),SUM,
     1       A(11,11),H(11,11),B(11,16),C(11,1),L2(11),G(11,11)
      DIMENSION INDEX(11,3)
      CHARACTER BUFFER(256)
C
C CREATING A NEW FILE FOR 11 CALIBRATION PARAMETERS
C
      OPEN (6,FILE='CALIB2.TXT',STATUS='NEW')
C
C IMAGE PROCESSING
C
      I=INIT(620)
      CALL AUTO
      CALL CHAN(1)
      CALL QUADM(1)
      CALL DQUAD(0)
   18 CALL SETIND(0)
      CALL CLEAR(0,7)
      CALL SBUF(1)
      WRITE (*,'(A\)') ' CHOOSE THRESHOLD VALUE : '
      READ (*,'(BN,I6)') I
      CALL SCALING(0,255,I,255,BUFFER)
      CALL SCALING(I+1,0,255,0,BUFFER)
      CALL LUTD(0,0,0,256,BUFFER)
      CALL SYNC(1)
      CALL SNAP(1)
      CALL SYNC(0)
      WRITE(*,'(A\)') ' IS THE PROCESSED IMAGE ACCEPTABLE (YES/NO:1/0)?'
      READ(*,'(BN,I6)') J
      IF (J.EQ.1) THEN
          GOTO 17
      ELSE
          GOTO 18
      ENDIF
C
C READING THE IMAGE  I X I  ( I : READING INCREAMENT )
C PROCESSING THE IMAGE BY USING THRESHOLD VALUE : 0 / 1
C
   17 WRITE (*,'(A\)') ' CHOOSE READING INCREAMENT :'
      READ (*,'(BN,I6)') M
      OPEN (2,FILE='TEM0.TXT',STATUS='NEW')
      J=1
      DO 5 Y=1,477,M
         DO 10 X=1,511,M
            I=IPIXR(X,Y)
            IF(I.EQ.255)THEN
               XCOR(J)=X
               YCOR(J)=Y
               WRITE (2,*) XCOR(J),YCOR(J)
               J=J+1
            ENDIF
```

```
   10    CONTINUE
    5 CONTINUE
C
C WINDOWING
C DELETION OF PIXELS WITH VALUE EQUAL TO 105
C CALCULATION OF TRANSITION POINTS IN EACH WINDOW
C CALCULATION OF CENTROID OF EACH MARKER :2-D COORDINATES
C
      REWIND 2
      OPEN (3,FILE='TEM1.TXT',STATUS='NEW')
      I1=0
      P=0
      O=1
      WRITE (*,'(A\)') ' CHOOSE WINDOW SIZE : '
      READ (*,'(BN,I6)') N
      DO 20 K=1,J-1
         READ (2,*) XCOR(K),YCOR(K)
         X2=0.0
         Y2=0.0
         DX1=0.0
         DO 40 Y=YCOR(K)-N,YCOR(K)+N
            DO 30 X=XCOR(K)-N,XCOR(K)+N
               I=IPIXR(X,Y)
               L(O)=I
               S=O-1
               IF(S.EQ.0)L(S)=0
               IF(L(O).EQ.105)L(O)=L(S)
               IF(L(O).NE.P)THEN
                  XP(O)=X
                  YP(O)=Y
                  T=O-1
                  IF(L(O).EQ.0)THEN
                     DX=XP(O)-XP(T)
                     X1=(XP(O)-DX/2.)*DX
                     Y1=YP(O)*DX
                     X2=X2+X1
                     Y2=Y2+Y1
                     DX1=DX1+DX
                  ENDIF
                  P=I
                  O=O+1
               ENDIF
   30       CONTINUE
   40    CONTINUE
         IF (DX1.LT.50) GOTO 20
         I1=I1+1
         X3(K)=X2/DX1
         Y3(K)=Y2/DX1
         WRITE (3,*) X3(K),Y3(K)
   20 CONTINUE
      IF (I1.LT.8) THEN
          WRITE (*,'(A\)') ' NUMBER OF DETECTED MARKERS IS LESS THAN 8 '
          GOTO 55
      ENDIF
C
C ELIMINATION OF REPEATED DATA
C
      OPEN (4,FILE='TEM2.TXT',STATUS='NEW')
      REWIND 3
      W=I1
      IF(W.GT.8)THEN
         GOTO 45
      ELSE
         DO 35 K=1,W
            READ (3,*) X3(K),Y3(K)
            WRITE (4,*) X3(K),Y3(K)
```

```
   35     CONTINUE
          GOTO 51
       ENDIF
   45  DO 46 K=1,W
           READ (3,*) X3(K),Y3(K)
   46  CONTINUE
       I2=0
       DO 50 M=1,W
          J=M+1
   60     IF(J.GT.W)GOTO 70
          DELX1=X3(J)-X3(M)
          DELY1=Y3(J)-Y3(M)
          IF(.NOT.((ABS(DELX1).LT.3.0).AND.(ABS(DELY1).LT.3.0)))THEN
             J=J+1
             GOTO 60
          ELSE
             GOTO 50
          ENDIF
   70     WRITE (4,*) X3(M),Y3(M)
          I2=I2+1
   50  CONTINUE
       IF (I2.NE.8) THEN
           WRITE (*,'(A\)') ' NUMBER OF DETECTED MARKERS IS NOT EQUAL TO
     18 '
           GOTO 55
       ENDIF
C
C READING THREE DIMENTIONAL COORDINATES OF CONTROL POINTS FROM SCREEN:
C X4(K),Y4(K),Z4(K)  ACCORDING TO THE ORDER OF MARKERS IN THE TWO
C DIMENTIONAL IMAGE
C
   51 WRITE (*,'(A\)')  ' ATTENTION : ALL THE INPUT DATA SHOULD BE IN ME
     1TERS WITH THREE DECIMAL POINTS'
      DO 100 K=1,8
         WRITE (*,*) K
         WRITE(*,'(A\)')  '                X4(K)=   '
         READ(*,'(BN,F6.3)') X4(K)
         WRITE (*,*) K
         WRITE(*,'(A\)')  '                Y4(K)=   '
         READ(*,'(BN,F6.3)') Y4(K)
         WRITE (*,*) K
         WRITE(*,'(A\)')  '                Z4(K)=   '
         READ(*,'(BN,F6.3)') Z4(K)
  100 CONTINUE
C
C DEFINING THE ELEMENTS OF THE MATRIX [P]:[16 X 11]
C
C                              T
C TRANSPOSE OF MATRIX [P] : [P]  =[R] : [11 X 16]
C
      REWIND 4
      DO 105 I=1,8
          READ (4,*) X3(I),Y3(I)
  105 CONTINUE
      DO 110 I=1,15,2
         J=(I+1)/2
         E(I,1)=X4(J)
         F(1,I)=X4(J)
         E(I,2)=Y4(J)
         F(2,I)=Y4(J)
         E(I,3)=Z4(J)
         F(3,I)=Z4(J)
         E(I,4)=1.0
         F(4,I)=1.0
         E(I,5)=0.0
         F(5,I)=0.0
```

```
         E(I,6)=0.0
         F(6,I)=0.0
         E(I,7)=0.0
         F(7,I)=0.0
         E(I,8)=0.0
         F(8,I)=0.0
         E(I,9)=-X3(J)*X4(J)
         F(9,I)=-X3(J)*X4(J)
         E(I,10)=-X3(J)*Y4(J)
         F(10,I)=-X3(J)*Y4(J)
         E(I,11)=-X3(J)*Z4(J)
         F(11,I)=-X3(J)*Z4(J)
  110 CONTINUE
      DO 120 I=2,16,2
         J=I/2
         E(I,1)=0.0
         F(1,I)=0.0
         E(I,2)=0.0
         F(2,I)=0.0
         E(I,3)=0.0
         F(3,I)=0.0
         E(I,4)=0.0
         F(4,I)=0.0
         E(I,5)=X4(J)
         F(5,I)=X4(J)
         E(I,6)=Y4(J)
         F(6,I)=Y4(J)
         E(I,7)=Z4(J)
         F(7,I)=Z4(J)
         E(I,8)=1.0
         F(8,I)=1.0
         E(I,9)=-Y3(J)*X4(J)
         F(9,I)=-Y3(J)*X4(J)
         E(I,10)=-Y3(J)*Y4(J)
         F(10,I)=-Y3(J)*Y4(J)
         E(I,11)=-Y3(J)*Z4(J)
         F(11,I)=-Y3(J)*Z4(J)
  120 CONTINUE
C
C DEFINING THE ELEMENTS OF THE MATRIX [Q]:[16 X 1]
C
      DO 130 I=1,15,2
         J=(I+1)/2
         D(I,1)=X3(J)
  130 CONTINUE
      DO 140 I=2,16,2
         J=I/2
         D(I,1)=Y3(J)
  140 CONTINUE
C                              T
C MATRIX MULTIPLICATION : [A]=[P] [P] : [11 X 11]
C
      DO 170 ROW=1,11
         DO 180 COL=1,11
            SUM=0.0
            DO 190 POSN=1,16
               SUM=SUM+F(ROW,POSN)*E(POSN,COL)
  190       CONTINUE
            A(ROW,COL)=SUM
  180    CONTINUE
  170 CONTINUE
      OPEN (11,FILE='MAT.TXT',STATUS='NEW')
      DO 191 J=1,11
          DO 192 I=1,11
              WRITE (11,*) A(I,J)
  192     CONTINUE
```

```
  191 CONTINUE
C                           -1
C MATRIX INVERTION : [H]=[A]    : [11 X 11]
C GAUSS-JORDAN METHOD
C
      N=11
      CALL MATINV(A,N)
      DO 221 J=1,11
          DO 222 I=1,11
             H(I,J)=A(I,J)
  222     CONTINUE
  221 CONTINUE
C
C REGENERATING  MATRIX  [A]
C
      REWIND 11
      DO 205 J =1,11
          DO 206 I=1,11
              READ (11,*) A(I,J)
  206     CONTINUE
  205 CONTINUE
C
C CALCULATION OF IDENTITY MATRIX : [I] = [A] [H]
C
      DO 201 ROW=1,11
          DO 202 COL=1,11
              SUM=0.0
              DO 203 POSN=1,11
                  SUM=SUM+A(ROW,POSN)* H(POSN,COL)
  203         CONTINUE
              G(ROW,COL)=SUM
  202     CONTINUE
  201 CONTINUE
      WRITE (*,'(A)') '    MATRIX   [I] : [11 X 11]   '
      DO 208 J=1,11
          DO 209 I=1,11
              WRITE (*,*) G(I,J)
  209     CONTINUE
  208 CONTINUE
C                                  T     -1    T
C MATRIX MULTIPLICATION : [B]=( [P] [P] )  [P]   : [11 X 16]
C
      DO 230 ROW=1,11
          DO 240 COL=1,16
              SUM=0.0
              DO 250 POSN=1,11
                  SUM=SUM+H(ROW,POSN)*F(POSN,COL)
  250         CONTINUE
              B(ROW,COL)=SUM
  240     CONTINUE
  230 CONTINUE
C                                  T     -1    T
C MATRIX MULTIPLICATION : [C]=( [P] [P] )  [P] [Q] : [11 X 1]
C
      DO 260 ROW=1,11
          COL=1
          SUM=0.0
          DO 280 POSN=1,16
              SUM=SUM+B(ROW,POSN)*D(POSN,COL)
  280     CONTINUE
          C(ROW,COL)=SUM
  260 CONTINUE
C
C DEFINING THE ELEMENTS OF THE  CALIBRATION SYSTEM : [L]
C
      DO 281 I=1,11
```

```
          L2(I)=C(I,1)
  281 CONTINUE
C
C STORING CALIBRATION PARAMETERS IN A FILE
C
      WRITE (*,'(A)') '  CALIBRATION PARAMETERS  L2(I) '
      DO 290 I=1,11
          WRITE(6,*)L2(I)
          WRITE(*,*)L2(I)
  290 CONTINUE
   55 CALL PEXIT
      STOP
      END
```

```
      PROGRAM REFRENCE MARKER ONE
$INCLUDE:'FORINTF.H'
C
C INITIALIZATION
C
      INTEGER*2 X4,Y4,I,J,K,P,Q,R,M,N,XCOR(100),YCOR(100),DELX,DELY,
     1          L(576),O,S,T,XP(100),YP(100),DX,U,V,W,FNO
      REAL X1,X2,DX1,X(5),Y1,Y2,Y(5),DELX1,DELY1
C
C IMAGE PROCESSING
C
      CHARACTER BUFFER(256)
      I=INIT(620)
      CALL AUTO
      CALL CHAN(1)
      CALL QUADM(1)
      CALL DQUAD(0)
   18 CALL SETIND(0)
      CALL CLEAR(0,7)
      CALL SBUF(1)
      WRITE (*,'(A\)') ' CHOOSE THRESHOLD VALUE : '
      READ (*,'(BN,I6)') I
      CALL SCALING(0,255,I,255,BUFFER)
      CALL SCALING(I+1,0,255,0,BUFFER)
      CALL LUTD(0,0,0,256,BUFFER)
      CALL SYNC(1)
      CALL SNAP(1)
      CALL SYNC(0)
      WRITE(*,'(A\)') ' IS THE PROCESSED IMAGE ACCEPTABLE (YES/NO:1/0)?'
      READ(*,'(BN,I6)') J
      IF (J.EQ.1) THEN
          GOTO 17
      ELSE
          GOTO 18
      ENDIF
C
C READING THE IMAGE 5 BY 5
C PROCESSING THE IMAGE BY USING THRESHOLD VALUE
C
   17 OPEN (11,FILE='TEMP0.TXT',STATUS='NEW')
      J=1
      DO 5 Y4=1,477,5
          DO 10 X4=1,511,5
              I=IPIXR(X4,Y4)
              IF(I.EQ.255)THEN
                 XCOR(J)=X4
                 YCOR(J)=Y4
                 WRITE (11,*) XCOR(J),YCOR(J)
                 J=J+1
              ENDIF
   10     CONTINUE
    5 CONTINUE
C
C WINDOWING
C DELETION OF PIXELS WITH VALUE EQUAL TO 105
C CALCULATION OF TRANSITION POINTS IN EACH WINDOW
C CALCULATION OF CENTROID OF EACH MARKER :2-D COORDINATES
C WRITING 2-D COORDINATES OF THE CENTROID OF EACH MARKER IN DATA FILE
C
      REWIND 11
```

```
      OPEN(14,FILE='TEMP1.TXT',STATUS='NEW')
      P=0
      O=1
      WRITE (*,'(A\)')  ' CHOOSE WINDOW SIZE '
      READ (*,'(BN,I6)') N
      DO 20 K=1,J-1
          READ (11,*) XCOR(K),YCOR(K)
          X2=0.0
          Y2=0.0
          DX1=0.0
          DO 40 Y4=YCOR(K)-N,YCOR(K)+N
              DO 30 X4=XCOR(K)-N,XCOR(K)+N
                  I=IPIXR(X4,Y4)
                  L(O)=I
                  S=O-1
                  IF(S.EQ.0)L(S)=0
                  IF(L(O).EQ.105)L(O)=L(S)
                  IF(L(O).NE.P)THEN
                     XP(O)=X4
                     YP(O)=Y4
                     T=O-1
                     IF(L(O).EQ.0)THEN
                        DX=XP(O)-XP(T)
                        X1=(XP(O)-DX/2.)*DX
                        Y1=YP(O)*DX
                        X2=X2+X1
                        Y2=Y2+Y1
                        DX1=DX1+DX
                     ENDIF
                     P=I
                     O=O+1
                  ENDIF
   30         CONTINUE
   40     CONTINUE
          X(K)=X2/DX1
          Y(K)=Y2/DX1
          WRITE(14,*)X(K),Y(K)
   20 CONTINUE
      IF (K-1.LT.1) THEN
          WRITE (*,'(A)') ' NUMBER OF DETECTED MARKERS IS LESS THAN  1 '
          GOTO 55
      ENDIF
C
C ELIMINATION OF REPEATED DATA
C
      OPEN (55,FILE='OUT0.TXT',STATUS='NEW')
      REWIND 14
      W=K-1
      IF(W.GT.1)THEN
         GOTO 45
      ELSE
         DO 35 J=1,W
             READ(14,*)X(J),Y(J)
             WRITE(55,*)X(J),Y(J)
   35    CONTINUE
         GOTO 55
      ENDIF
   45 DO 46 M=1,W
          READ (14,*) X(M),Y(M)
   46 CONTINUE
      I2=0
      DO 50 M=1,W
          J=M+1
   60     IF (J.GT.W) GOTO 70
          DELX1=X(J)-X(M)
          DELY1=Y(J)-Y(M)
```

```
        IF(.NOT.((ABS(DELX1).LT.1.0).AND.(ABS(DELY1).LT.1.0)))THEN
           J=J+1
           GOTO 60
        ELSE
           GOTO 50
        ENDIF
70      XR=X(M)
        YR=Y(M)
        I2=I2+1
        WRITE (*,*) XR,YR
50 CONTINUE
   IF (I2.GT.1)THEN
        WRITE (*,'(A\)') 'NUMBER OF DETECED MARKERS IS GREATER THAN 1'
        GOTO 55
   ELSE
        WRITE (55,*) XR,YR
   ENDIF
55 CALL PEXIT
   STOP
   END
```

```
      PROGRAM REFRENCE MARKER TWO
$INCLUDE:'FORINTF.H'
C
C INITIALIZATION
C
      INTEGER*2 X4,Y4,I,J,K,P,Q,R,M,N,XCOR(100),YCOR(100),DELX,DELY,
     1          L(576),O,S,T,XP(100),YP(100),DX,U,V,W,FNO
      REAL X1,X2,DX1,X(5),Y1,Y2,Y(5),DELX1,DELY1
C
C IMAGE PROCESSING
C
      CHARACTER BUFFER(256)
      I=INIT(620)
      CALL AUTO
      CALL CHAN(1)
      CALL QUADM(1)
      CALL DQUAD(0)
   18 CALL SETIND(0)
      CALL CLEAR(0,7)
      CALL SBUF(1)
      WRITE (*,'(A\)') ' CHOOSE THRESHOLD VALUE : '
      READ (*,'(BN,I6)') I
      CALL SCALING(0,255,I,255,BUFFER)
      CALL SCALING(I+1,0,255,0,BUFFER)
      CALL LUTD(0,0,0,256,BUFFER)
      CALL SYNC(1)
      CALL SNAP(1)
      CALL SYNC(0)
      WRITE(*,'(A\)') ' IS THE PROCESSED IMAGE ACCEPTABLE (YES/NO:1/0)?'
      READ(*,'(BN,I6)') J
      IF (J.EQ.1) THEN
          GOTO 17
      ELSE
          GOTO 18
      ENDIF
C
C READING THE IMAGE 5 BY 5
C PROCESSING THE IMAGE BY USING THRESHOLD VALUE
C
   17 OPEN (11,FILE='TEMP0.TXT',STATUS='NEW')
      J=1
      DO 5 Y4=1,477,5
          DO 10 X4=1,511,5
              I=IPIXR(X4,Y4)
              IF(I.EQ.255)THEN
                 XCOR(J)=X4
                 YCOR(J)=Y4
                 WRITE (11,*) XCOR(J),YCOR(J)
                 J=J+1
              ENDIF
   10     CONTINUE
    5 CONTINUE
C
C WINDOWING
C DELETION OF PIXELS WITH VALUE EQUAL TO 105
C CALCULATION OF TRANSITION POINTS IN EACH WINDOW
C CALCULATION OF CENTROID OF EACH MARKER :2-D COORDINATES
C WRITING 2-D COORDINATES OF THE CENTROID OF EACH MARKER IN DATA FILE
C
      REWIND 11
```

```
       OPEN(14,FILE='TEMP1.TXT',STATUS='NEW')
       P=0
       O=1
       WRITE (*,'(A\)') ' CHOOSE WINDOW SIZE :'
       READ (*,'(BN,I6)') N
       DO 20 K=1,J-1
           READ (11,*) XCOR(K),YCOR(K)
           X2=0.0
           Y2=0.0
           DX1=0.0
           DO 40 Y4=YCOR(K)-N,YCOR(K)+N
               DO 30 X4=XCOR(K)-N,XCOR(K)+N
                   I=IPIXR(X4,Y4)
                   L(O)=I
                   S=O-1
                   IF(S.EQ.0)L(S)=0
                   IF(L(O).EQ.105)L(O)=L(S)
                   IF(L(O).NE.P)THEN
                      XP(O)=X4
                      YP(O)=Y4
                      T=O-1
                      IF(L(O).EQ.0)THEN
                         DX=XP(O)-XP(T)
                         X1=(XP(O)-DX/2.)*DX
                         Y1=YP(O)*DX
                         X2=X2+X1
                         Y2=Y2+Y1
                         DX1=DX1+DX
                     ENDIF
                     P=I
                     O=O+1
                  ENDIF
   30          CONTINUE
   40     CONTINUE
          X(K)=X2/DX1
          Y(K)=Y2/DX1
          WRITE(14,*)X(K),Y(K)
   20 CONTINUE
      IF (K-1.LT.1) THEN
          WRITE (*,'(A)') ' NUMBER OF DETECTED MARKERS IS LESS THAN   1 '
          GOTO 55
      ENDIF
C
C ELIMINATION OF REPEATED DATA
C
      OPEN (56,FILE='OUT00.TXT',STATUS='NEW')
      REWIND 14
      W=K-1
      IF(W.GT.1)THEN
         GOTO 45
      ELSE
         DO 35 J=1,W
             READ(14,*)X(J),Y(J)
             WRITE(56,*)X(J),Y(J)
   35    CONTINUE
         GOTO 55
      ENDIF
   45 DO 46 M=1,W
          READ (14,*) X(M),Y(M)
   46 CONTINUE
      I2=0
      DO 50 M=1,W
          J=M+1
   60     IF (J.GT.W) GOTO 70
          DELX1=X(J)-X(M)
          DELY1=Y(J)-Y(M)
```

```
       IF(.NOT.((ABS(DELX1).LT.1.0).AND.(ABS(DELY1).LT.1.0)))THEN
          J=J+1
          GOTO 60
       ELSE
          GOTO 50
       ENDIF
70     XR=X(M)
       YR=Y(M)
       I2=I2+1
       WRITE (*,*) XR,YR
50 CONTINUE
   IF (I2.GT.1)THEN
       WRITE (*,'(A\)') 'NUMBER OF DETECED MARKERS IS GREATER THAN 1'
       GOTO 55
   ELSE
       WRITE (56,*) XR,YR
   ENDIF
55 CALL FEXIT
   STOP
   END
```

```
      PROGRAM EMPTY DATA FILE
$INCLUDE:'FORINTF.H'
C
C CREATING AN EMPTY DATA FILE :  'OUT1.TXT'  FOR THE PROGRAM IMAGE1.FOR
C
      OPEN (30,FILE='OUT1.TXT',STATUS='NEW')
      CALL PEXIT
      STOP
      END


      PROGRAM EMPTY DATA FILE
$INCLUDE:'FORINTF.H'
C
C CREATING AN EMPTY DATA FILE :  'OUT2.TXT'  FOR THE PROGRAM IMAGE2.FOR
C
      OPEN (35,FILE='OUT2.TXT',STATUS='NEW')
      CALL PEXIT
      STOP
      END


      PROGRAM EMPTY DATA FILE
$INCLUDE:'FORINTF.H'
C
C CREATING AN EMPTY DATA FILE :  'XYREF1.TXT'  FOR THE PROGRAM IMAGE1.FOR
C
      OPEN (19,FILE='XYREF1.TXT',STATUS='NEW')
      CALL PEXIT
      STOP
      END


      PROGRAM EMPTY DATA FILE
$INCLUDE:'FORINTF.H'
C
C CREATING AN EMPTY DATA FILE :  'XYREF2.TXT'  FOR THE PROGRAM IMAGE2.FOR
C
      OPEN (20,FILE='XYREF2.TXT',STATUS='NEW')
      CALL PEXIT
      STOP
      END


      PROGRAM EMPTY DATA FILE
$INCLUDE:'FORINTF.H'
      OPEN (25,FILE='FRNO1.TXT',STATUS='NEW')
      CALL PEXIT
      STOP
      END


      PROGRAM EMPTY DATA FILE
$INCLUDE:'FORINTF.H'
      OPEN (26,FILE='FRNO2.TXT',STATUS='NEW')
      CALL PEXIT
      STOP
      END
```

```
      PROGRAM IMAGE REDUCTION ONE
$INCLUDE:'FORINTF.H'
C
C INITIALIZATION
C
      INTEGER*2 X4,Y4,I,J,K,P,Q,R,M,N,XCOR(100),YCOR(100),DELX,DELY,
     1          L(576),O,S,T,XP(100),YP(100),DX,U,V,W,FNO,FRNO
      REAL X1,X2,DX1,X(7,100),Y1,Y2,Y(7,100),DELX1,DELY1,XN(100),
     1     YN(100)
C
C IMAGE PROCESSING
C
      CHARACTER BUFFER(256)
      I=INIT(620)
      CALL AUTO
      CALL CHAN(1)
      CALL QUADM(1)
      CALL DQUAD(0)
      DO 55 N=1,500
   18 CALL SETIND(0)
      CALL CLEAR(0,7)
      CALL SETWIN(35,1,511,477)
      CALL SBUF(1)
      WRITE (*,'(A\)') ' CHOOSE THRESHOLD VALUE : '
      READ (*,'(BN,I6)') I
      CALL SCALING(0,255,I,255,BUFFER)
      CALL SCALING(I+1,0,255,0,BUFFER)
      CALL LUTD(0,0,0,256,BUFFER)
      CALL SYNC(1)
      CALL SNAP(1)
      CALL SYNC(0)
      WRITE(*,'(A\)') ' IS THE PROCESSED IMAGE ACCEPTABLE (YES/NO:1/0)?'
      READ(*,'(BN,I6)') J
      IF (J.EQ.1) THEN
          GOTO 17
      ELSE
          GOTO 18
      ENDIF
C
C POSITIONING THE FILE AT THE END OF THE OLD DATA FILE
C
   17 OPEN(30,FILE='OUT1.TXT')
      FNO=0
      DO 2 J=1,100
          DO 3 I=1,7
              READ (30,*,END=4) X(I,J),Y(I,J)
    3     CONTINUE
          FNO=FNO+1
    2 CONTINUE
    4 BACKSPACE 30
      FNO=FNO+1
C
C READING THE IMAGE M BY M (M : READING INCREAMENT)
C PROCESSING THE IMAGE BY USING THRESHOLD VALUE
C
      WRITE (*,'(A\)')  'CHOOSE READING INCREAMENT : '
      READ (*,'(BN,I6)') M
      OPEN (12,FILE='TEMP2.TXT',STATUS='NEW')
      J=1
```

```
      DO 5 Y4=1,477,M
          DO 10 X4=1,511,M
              I=IPIXR(X4,Y4)
              IF(I.EQ.255)THEN
                 XCOR(J)=X4
                 YCOR(J)=Y4
                 WRITE (12,*) XCOR(J),YCOR(J)
                 J=J+1
              ENDIF
   10     CONTINUE
    5 CONTINUE
C
C WINDOWING
C DELETION OF PIXELS WITH VALUE EQUAL TO 105
C CALCULATION OF TRANSITION POINTS IN EACH WINDOW
C CALCULATION OF CENTROID OF EACH MARKER :2-D COORDINATES
C WRITING 2-D COORDINATES OF THE CENTROID OF EACH MARKER IN DATA FILE
C
      REWIND 12
      OPEN(15,FILE='TEMP3.TXT',STATUS='NEW')
      I1=0
      P=0
      O=1
      WRITE (*,'(A\)')  'CHOOSE WINDOW SIZE :'
      READ (*,'(BN,I6)') N
      DO 20 K=1,J-1
          READ (12,*) XCOR(K),YCOR(K)
          X2=0.0
          Y2=0.0
          DX1=0.0
          DO 40 Y4=YCOR(K)-N,YCOR(K)+N
              DO 30 X4=XCOR(K)-N,XCOR(K)+N
                  I=IPIXR(X4,Y4)
                  L(O)=I
                  S=O-1
                  IF(S.EQ.0)L(S)=0
                  IF(L(O).EQ.105)L(O)=L(S)
                  IF(L(O).NE.P)THEN
                     XP(O)=X4
                     YP(O)=Y4
                     T=O-1
                     IF(L(O).EQ.0)THEN
                        DX=XP(O)-XP(T)
                        X1=(XP(O)-DX/2.)*DX
                        Y1=YP(O)*DX
                        X2=X2+X1
                        Y2=Y2+Y1
                        DX1=DX1+DX
                     ENDIF
                     P=I
                     O=O+1
                  ENDIF
   30         CONTINUE
   40     CONTINUE
          IF (DX1.LT.15) GOTO 20
          I1=I1+1
          XN(I1)=X2/DX1
          YN(I1)=Y2/DX1
          WRITE(15,*)XN(I1),YN(I1)
   20 CONTINUE
      IF (I1.LT.8) THEN
          WRITE (*,'(A)') ' NUMBER OF DETECTED MARKERS IS LESS THAN  8 '
          GOTO 55
      ENDIF
C
C ELIMINATION OF REPEATED DATA
```

```
C
      REWIND 15
      W=I1
   45 DO 46 M=1,W
          READ (15,*) XN(M),YN(M)
   46 CONTINUE
      OPEN (16,FILE='TEMP4.TXT',STATUS='NEW')
      I2=0
      DO 50 M=1,W
          J=M+1
   60     IF(J.GT.W)GOTO 70
          DELX1=XN(J)-XN(M)
          DELY1=YN(J)-YN(M)
          IF(.NOT.((ABS(DELX1).LT.4.0).AND.(ABS(DELY1).LT.4.0)))THEN
             J=J+1
             GOTO 60
          ELSE
             GOTO 50
          ENDIF
   70     I2=I2+1
          WRITE(16,*)XN(M),YN(M)
   50 CONTINUE
      IF (I2.EQ.8) THEN
          GOTO 51
      ELSE
          WRITE (*,'(A\)') ' NUMBER OF DETECTED MARKERS IS NOT EQUAL TO
     1    8 '
          GOTO 55
      ENDIF
   51 REWIND 16
      OPEN (19,FILE='XYREF1.TXT')
      DO 54 I=1,100
         READ (19,*,END=80) XN(I2),YN(I2)
   54 CONTINUE
   80 BACKSPACE 19
      DO 52 I=1,I2
         READ (16,*) XN(I),YN(I)
   52 CONTINUE
      WRITE (*,*) XN(I2),YN(I2)
      WRITE (*,'(A\)') '  IS THE COORD. OF REF. MARKER CORRECT (YES/NO :
     1 1/0)? '
      READ (*,'(BN,I6)') I
      IF (I.EQ.1) THEN
          GOTO 71
      ELSE
          GOTO 55
      ENDIF
   71 WRITE (19,*) XN(I2),YN(I2)
      OPEN (55,FILE='OUT0.TXT')
      READ (55,*) XR,YR
      DO 53 I=1,I2-1
         X(I,FNO)=XN(I)-(XR-XN(I2))
         Y(I,FNO)=YN(I)+(YR-YN(I2))
         WRITE (30,*) X(I,FNO),Y(I,FNO)
         WRITE (*,*) X(I,FNO),Y(I,FNO)
   53 CONTINUE
      WRITE (*,*) FNO
      OPEN (25,FILE='FRNO1.TXT')
      DO 15 I=1,100
         READ (25,*,END=16) FRNO
   15 CONTINUE
   16 BACKSPACE 25
      WRITE (*,'(A\)') 'THE FRAME NUMBER OF THE PROCESSED IMAGE IS :
     1FRNO=  '
      READ (*,'(BN,I6)') FRNO
      WRITE (25,*) FRNO
```

```
55 CONTINUE
56 CALL PEXIT
   STOP
   END
```

```
      PROGRAM IMAGE REDUCTION TWO
$INCLUDE:'FORINTF.H'
C
C INITIALIZATION
C
      INTEGER*2 X4,Y4,I,J,K,P,Q,R,M,N,XCOR(100),YCOR(100),DELX,DELY,
     1          L(576),O,S,T,XP(100),YP(100),DX,U,V,W,FNO,FRNO
      REAL X1,X2,DX1,X(7,100),Y1,Y2,Y(7,100),DELX1,DELY1,XN(100),
     1     YN(100)
C
C IMAGE PROCESSING
C
      CHARACTER BUFFER(256)
      I=INIT(620)
      CALL AUTO
      CALL CHAN(1)
      CALL QUADM(1)
      CALL DQUAD(0)
      DO 55 N=1,500
   18 CALL SETIND(0)
      CALL CLEAR(0,7)
      CALL SBUF(1)
      WRITE (*,'(A\)') 'CHOOSE THRESHOLD VALUE : '
      READ (*,'(BN,I6)') I
      CALL SCALING(0,255,I,255,BUFFER)
      CALL SCALING(I+1,0,255,0,BUFFER)
      CALL LUTD(0,0,0,256,BUFFER)
      CALL SYNC(1)
      CALL SNAP(1)
      CALL SYNC(0)
      WRITE(*,'(A\)') ' IS THE PROCESSED IMAGE ACCEPTABLE (YES/NO:1/0)?'
      READ(*,'(BN,I6)') J
      IF (J.EQ.1) THEN
          GOTO 17
      ELSE
          GOTO 18
      ENDIF
C
C POSITIONING THE FILE AT THE END OF THE OLD DATA FILE
C
   17 OPEN(35,FILE='OUT2.TXT')
      FNO=0
      DO 2 J=1,100
          DO 3 I=1,7
              READ (35,*,END=4) X(I,J),Y(I,J)
    3     CONTINUE
          FNO=FNO+1
    2 CONTINUE
    4 BACKSPACE 35
      FNO=FNO+1
C
C READING THE IMAGE M BY M (M : READING INCREAMENT )
C PROCESSING THE IMAGE BY USING THRESHOLD VALUE
C
      WRITE (*,'(A\)')  ' CHOOSE READING INCREAMENT : '
      READ (*,'(BN,I6)')  M
      OPEN (12,FILE='TEMP2.TXT',STATUS='NEW')
      J=1
      DO 5 Y4=1,477,M
```

```
          DO 10 X4=1,511,M
              I=IFIXR(X4,Y4)
              IF(I.EQ.255)THEN
                 XCOR(J)=X4
                 YCOR(J)=Y4
                 WRITE (12,*) XCOR(J),YCOR(J)
                 J=J+1
              ENDIF
   10     CONTINUE
    5 CONTINUE
C
C WINDOWING
C DELETION OF PIXELS WITH VALUE EQUAL TO 105
C CALCULATION OF TRANSITION POINTS IN EACH WINDOW
C CALCULATION OF CENTROID OF EACH MARKER :2-D COORDINATES
C WRITING 2-D COORDINATES OF THE CENTROID OF EACH MARKER IN DATA FILE
C
      REWIND 12
      OPEN(15,FILE='TEMP3.TXT',STATUS='NEW')
      I1=0
      P=0
      O=1
      WRITE (*,'(A\)') ' CHOOSE WINDOW SIZE : '
      READ (*,'(BN,I6)') N
      DO 20 K=1,J-1
          READ (12,*) XCOR(K),YCOR(K)
          X2=0.0
          Y2=0.0
          DX1=0.0
          DO 40 Y4=YCOR(K)-N,YCOR(K)+N
              DO 30 X4=XCOR(K)-N,XCOR(K)+N
                  I=IFIXR(X4,Y4)
                  L(O)=I
                  S=O-1
                  IF(S.EQ.0)L(S)=0
                  IF(L(O).EQ.105)L(O)=L(S)
                  IF(L(O).NE.P)THEN
                     XP(O)=X4
                     YP(O)=Y4
                     T=O-1
                     IF(L(O).EQ.0)THEN
                        DX=XP(O)-XP(T)
                        X1=(XP(O)-DX/2.)*DX
                        Y1=YP(O)*DX
                        X2=X2+X1
                        Y2=Y2+Y1
                        DX1=DX1+DX
                     ENDIF
                     P=I
                     O=O+1
                  ENDIF
   30         CONTINUE
   40     CONTINUE
          IF (DX1.LT.15) GOTO 20
          I1=I1+1
          XN(I1)=X2/DX1
          YN(I1)=Y2/DX1
          WRITE(15,*)XN(I1),YN(I1)
   20 CONTINUE
      IF (I1.LT.8) THEN
          WRITE (*,'(A)')  ' NUMBER OF DETECTED MARKERS IS LESS THAN  8
          GOTO 55
      ENDIF
C
C ELIMINATION OF REPEATED DATA
C
```

```
   REWIND 15
   W=I1
45 DO 46 M=1,W
       READ (15,*) XN(M),YN(M)
46 CONTINUE
   OPEN (16,FILE='TEMP4.TXT',STATUS='NEW')
   I2=0
   DO 50 M=1,W
       J=M+1
60     IF(J.GT.W)GOTO 70
       DELX1=XN(J)-XN(M)
       DELY1=YN(J)-YN(M)
       IF(.NOT.((ABS(DELX1).LT.4.0).AND.(ABS(DELY1).LT.4.0)))THEN
          J=J+1
          GOTO 60
       ELSE
          GOTO 50
       ENDIF
70     I2=I2+1
       WRITE(16,*)XN(M),YN(M)
50 CONTINUE
   IF (I2.EQ.8) THEN
       GOTO 51
   ELSE
       WRITE (*,'(A\)') ' NUMBER OF DETECTED MARKERS IS NOT EQUAL TO
  1    8 '
       GOTO 55
   ENDIF
51 REWIND 16
   OPEN (20,FILE='XYREF2.TXT')
   DO 54 I=1,100
      READ (20,*,END=80) XN(I2),YN(I2)
54 CONTINUE
80 BACKSPACE 20
   DO 52 I=1,I2
      READ (16,*) XN(I),YN(I)
52 CONTINUE
   WRITE (*,*) XN(I2),YN(I2)
   WRITE (*,'(A\)') 'IS THE COORD. OF REF. MARKER CORRECT (YES/NO :
  1 1,0)? '
   READ (*,'(BN,I6)') I
   IF (I.EQ.1) THEN
       GOTO 71
   ELSE
       GOTO 55
   ENDIF
71 WRITE (20,*) XN(I2),YN(I2)
   OPEN (56,FILE='OUT00.TXT')
   READ (56,*) XR,YR
   DO 53 I=1,I2-1
      X(I,FNO)=XN(I)-(XR-XN(I2))
      Y(I,FNO)=YN(I)+(YR-YN(I2))
      WRITE (35,*) X(I,FNO),Y(I,FNO)
      WRITE (*,*) X(I,FNO),Y(I,FNO)
53 CONTINUE
   WRITE (*,*) FNO
   OPEN (26,FILE='FRNO2.TXT')
   DO 15 I=1,100
      READ (26,*,END=16) FRNO
15 CONTINUE
16 BACKSPACE 26
   WRITE (*,'(A\)') 'THE FRAME NUMBER OF THE PROCESSED IMAGE IS :
  1FRNO= '
   READ (*,'(BN,I6)') FRNO
   WRITE (26,*) FRNO
55 CONTINUE
56 CALL PEXIT
   STOP
   END
```

```
      PROGRAM MARKER TRACKING ONE
$INCLUDE:'FORINTF.H'
$LARGE
C
C INITIALIZATION
C
      INTEGER*2 MNO,FNO,NMNO,FNO1,M(7)
      REAL X(7,100),Y(7,100),XN1(7,100),YN1(7,100),XP(7,100),YP(7,
     1     100),DIST(7,7),BIG,AX(7,100),AY(7,100),BX(7,100),BY(7,
     1     100),LARGE,DISTA(7,7),T
C
C READING FROM OLD DATA FILE=30 INTO MEMORY
C
      OPEN (30,FILE='OUT1.TXT')
      FNO1=0
      DO 10 FNO=1,100
         DO 20 MNO=1,7
            READ (30,*,END=4) X(MNO,FNO),Y(MNO,FNO)
   20    CONTINUE
         FNO1=FNO1+1
   10 CONTINUE
    4 WRITE (*,*)FNO1
C
C CREATING FINAL TWO DIMENTIONAL DATA FILE
C
C INTERACTIVE IDENTIFICATION  OF MARKERS IN THE FIRST TWO FRAMES
C
      OPEN (40,FILE='NOUT1.TXT',STATUS='NEW')
      OPEN (77,FILE='TEMP20.TXT',STATUS='NEW')
      DO 30 FNO=1,2
         DO 40 MNO=1,7
            WRITE(*,'(A\)') '  ASSIGN CORRECT MARKER NUMBER: NMNO=    '
            READ (*,'(BN,I6)') NMNO
            XN1(NMNO,FNO)=X(MNO,FNO)
            YN1(NMNO,FNO)=Y(MNO,FNO)
   40    CONTINUE
         DO 42 NMNO=1,7
            WRITE (40,*) XN1(NMNO,FNO),YN1(NMNO,FNO)
            WRITE (77,*) XN1(NMNO,FNO),YN1(NMNO,FNO)
   42    CONTINUE
   30 CONTINUE
C
C IDENTIFICATION OF MARKERS IN THIRD FRAME:USING TWO DIMENTIONAL
C LINEAR EXTRAPOLATION AND NEAREST NEIGHBOUR CRITERION
C
      REWIND 77
      DO 45 FNO=1,2
         DO 46 NMNO=1,7
            READ (77,*) XN1(NMNO,FNO),YN1(NMNO,FNO)
   46    CONTINUE
   45 CONTINUE
      OPEN (78,FILE='TEMP21.TXT',STATUS='NEW')
      DO 51 FNO=3
         DO 50 K=1,7
            XP(K,FNO)=XN1(K,FNO-2)+2.*(XN1(K,FNO-1)-XN1(K,FNO-2))
            YP(K,FNO)=YN1(K,FNO-2)+2.*(YN1(K,FNO-1)-YN1(K,FNO-2))
   50    CONTINUE
         OPEN (22,FILE='TEMP22.TXT',STATUS='NEW')
         L=0
         DO 60 K=1,7
```

```
            BIG=10000.0
            DO 70 J=1,7
               IF (K.EQ.1) GOTO 72
               REWIND 22
               IF (K.EQ.2) THEN
                   READ (22,*) M(1)
                   IF (J.EQ.M(1)) GOTO 70
                   IF (J.NE.M(1)) GOTO 72
               ENDIF
               DO 71 I=1,K-1
                  READ (22,*,END=72) M(I)
                  IF ((J.EQ.7).AND.(M(I).EQ.7)) GOTO 71
                  IF (J.EQ.M(I)) GOTO 70
   71          CONTINUE
   72          DIST(K,J)=((XP(K,FNO)-X(J,FNO))**2.+(YP(K,FNO)-Y(J,FNO))
     1                   **2.)**(1./2.)
               IF (DIST(K,J).LT.BIG) THEN
                   BIG=DIST(K,J)
                   N=J
               ELSE
                   BIG=BIG
               ENDIF
   70      CONTINUE
           L=L+1
           M(L)=N
           WRITE (22,*) M(L)
           XN1(K,FNO)=X(N,FNO)
           YN1(K,FNO)=Y(N,FNO)
           WRITE(40,*) XN1(K,FNO),YN1(K,FNO)
           WRITE (78,*) XN1(K,FNO),YN1(K,FNO)
   60    CONTINUE
   51 CONTINUE
C
C IDENTIFICATION OF MARKERS :USING THREE-POINT,TWO DIMENTIONAL
C LINEAR LEAST SQUARES APPROXIMATION AND NEAREST NEIGHBOUR CRITERION
C
      REWIND 77
      REWIND 78
      DO 65 FNO=1,2
         DO 66 NMNO=1,7
            READ (77,*) XN1(NMNO,FNO),YN1(NMNO,FNO)
   66    CONTINUE
   65 CONTINUE
      DO 67 NMNO=1,7
         READ (78,*) XN1(NMNO,3),YN1(NMNO,3)
   67 CONTINUE
      DO 85 FNO=4,FNO1
             DO 90 K=1,7
                AX(K,FNO)=(-XN1(K,FNO-3)+XN1(K,FNO-1))/2.
                AY(K,FNO)=(-YN1(K,FNO-3)+YN1(K,FNO-1))/2.
                BX(K,FNO)=(XN1(K,FNO-3)+XN1(K,FNO-2)+XN1(K,FNO-1)-
     1                      6.*AX(K,FNO))/3.
                BY(K,FNO)=(YN1(K,FNO-3)+YN1(K,FNO-2)+YN1(K,FNO-1)-
     1                     6.*AY(K,FNO))/3.
                XP(K,FNO)=4.*AX(K,FNO)+BX(K,FNO)
                YP(K,FNO)=4.*AY(K,FNO)+BY(K,FNO)
   90        CONTINUE
             OPEN (23,FILE='TEMP23.TXT',STATUS='NEW')
             L=0
             DO 100 K=1,7
                LARGE=10000.0
                DO 110 J=1,7
                   IF (K.EQ.1) GOTO 96
                   REWIND 23
                   IF (K.EQ.2) THEN
                       READ (23,*) M(1)
```

```
                       IF (J.EQ.M(1)) GOTO 110
                       IF (J.NE.M(1)) GOTO 96
                   ENDIF
                   DO 95 I=1,K-1
                      O=K-1
                      READ (23,*,END=96) M(I)
                      IF ((J.EQ.7).AND.(M(I).EQ.7)) GOTO 95
                      IF (J.EQ.M(I)) GOTO 110
 95                CONTINUE
 96                DISTA(K,J)=((XP(K,FNO)-X(J,FNO))**2.+(YP(K,FNO)-Y(J,
     1                          FNO))**2.)**(1./2.)
                   IF (DISTA(K,J).LT.LARGE) THEN
                       LARGE=DISTA(K,J)
                       N=J
                   ELSE
                       LARGE=LARGE
                   ENDIF
110             CONTINUE
                L=L+1
                M(L)=N
                WRITE (23,*) M(L)
                XN1(K,FNO)=X(N,FNO)
                YN1(K,FNO)=Y(N,FNO)
                WRITE (40,*) XN1(K,FNO),YN1(K,FNO)
100          CONTINUE
 85   CONTINUE
      REWIND 23
      DO 150 I=1,7
         READ (23,*,END=151) M(I)
150   CONTINUE
151   CALL FEXIT
      STOP
      END
```

```
      PROGRAM MARKER TRACKING TWO
$INCLUDE:'FORINTF.H'
$LARGE
C
C INITIALIZATION
C
      INTEGER*2 MNO,FNO,NMNO,FNO1,M(7)
      REAL X(7,1000),Y(7,1000),XN2(7,1000),YN2(7,1000),XP(7,1000),YP(7,
     1     1000),DIST(7,7),BIG,AX(7,1000),AY(7,1000),BX(7,1000),BY(7,
     1     1000),LARGE,DISTA(7,7),T
C
C READING FROM OLD DATA FILE=35 INTO MEMORY
C
      OPEN (35,FILE='OUT2.TXT')
      FNO1=0
      DO 10 FNO=1,1000
         DO 20 MNO=1,7
            READ (35,*,END=4) X(MNO,FNO),Y(MNO,FNO)
   20    CONTINUE
         FNO1=FNO1+1
   10 CONTINUE
    4 WRITE (*,*)FNO1
C
C CREATING FINAL TWO DIMENTIONAL DATA FILE
C
C INTERACTIVE IDENTIFICATION  OF MARKERS IN THE FIRST TWO FRAMES
C
      OPEN (45,FILE='NOUT2.TXT',STATUS='NEW')
      OPEN (77,FILE='TEMP20.TXT',STATUS='NEW')
      DO 30 FNO=1,2
         DO 40 MNO=1,7
            WRITE(*,'(A\)') '  ASSIGN CORRECT MARKER NUMBER: NMNO=    '
            READ (*,'(BN,I6)') NMNO
            XN2(NMNO,FNO)=X(MNO,FNO)
            YN2(NMNO,FNO)=Y(MNO,FNO)
   40    CONTINUE
         DO 42 NMNO=1,7
            WRITE (45,*) XN2(NMNO,FNO),YN2(NMNO,FNO)
            WRITE (77,*) XN2(NMNO,FNO),YN2(NMNO,FNO)
   42    CONTINUE
   30 CONTINUE
C
C IDENTIFICATION OF MARKERS IN THIRD FRAME:USING TWO DIMENTIONAL
C LINEAR EXTRAPOLATION AND NEAREST NEIGHBOUR CRITERION
C
      REWIND 77
      DO 45 FNO=1,2
         DO 46 NMNO=1,7
            READ (77,*) XN2(NMNO,FNO),YN2(NMNO,FNO)
   46    CONTINUE
   45 CONTINUE
      OPEN (78,FILE='TEMP21.TXT',STATUS='NEW')
      DO 51 FNO=3
         DO 50 K=1,7
            XP(K,FNO)=XN2(K,FNO-2)+2.*(XN2(K,FNO-1)-XN2(K,FNO-2))
            YP(K,FNO)=YN2(K,FNO-2)+2.*(YN2(K,FNO-1)-YN2(K,FNO-2))
   50    CONTINUE
         OPEN (22,FILE='TEMP22.TXT',STATUS='NEW')
         L=0
         DO 60 K=1,7
```

```
           BIG=10000.0
           DO 70 J=1,7
              IF (K.EQ.1) GOTO 72
              REWIND 22
              IF (K.EQ.2) THEN
                  READ (22,*) M(1)
                  IF (J.EQ.M(1)) GOTO 70
                  IF (J.NE.M(1)) GOTO 72
              ENDIF
              DO 71 I=1,K-1
                 READ (22,*,END=72) M(I)
                 IF ((J.EQ.7).AND.(M(I).EQ.7)) GOTO 71
   71         CONTINUE
   72         DIST(K,J)=((XP(K,FNO)-X(J,FNO))**2.+(YP(K,FNO)-Y(J,FNO))
     1                  **2.)**(1./2.)
              IF (J.EQ.1) BIG=10000.0
              IF (DIST(K,J).LT.BIG) THEN
                  BIG=DIST(K,J)
                  N=J
              ELSE
                  BIG=BIG
              ENDIF
   70      CONTINUE
           L=L+1
           M(L)=N
           WRITE (22,*) M(L)
           XN2(K,FNO)=X(N,FNO)
           YN2(K,FNO)=Y(N,FNO)
           WRITE(45,*) XN2(K,FNO),YN2(K,FNO)
           WRITE (78,*) XN2(K,FNO),YN2(K,FNO)
   60    CONTINUE
   51 CONTINUE
C
C IDENTIFICATION OF MARKERS :USING THREE-POINT,TWO DIMENTIONAL
C LINEAR LEAST SQUARES APPROXIMATION AND NEAREST NEIGHBOUR CRITERION
C
      REWIND 77
      REWIND 78
      DO 65 FNO=1,2
         DO 66 NMNO=1,7
            READ (77,*) XN2(NMNO,FNO),YN2(NMNO,FNO)
   66    CONTINUE
   65 CONTINUE
      DO 67 NMNO=1,7
         READ (78,*) XN2(NMNO,3),YN2(NMNO,3)
   67 CONTINUE
      DO 85 FNO=4,FNO1
             DO 90 K=1,7
                AX(K,FNO)=(-XN2(K,FNO-3)+XN2(K,FNO-1))/2.
                AY(K,FNO)=(-YN2(K,FNO-3)+YN2(K,FNO-1))/2.
                BX(K,FNO)=(XN2(K,FNO-3)+XN2(K,FNO-2)+XN2(K,FNO-1)-
     1                     6.*AX(K,FNO))/3.
                BY(K,FNO)=(YN2(K,FNO-3)+YN2(K,FNO-2)+YN2(K,FNO-1)-
     1                     6.*AY(K,FNO))/3.
                XP(K,FNO)=4.*AX(K,FNO)+BX(K,FNO)
                YP(K,FNO)=4.*AY(K,FNO)+BY(K,FNO)
   90        CONTINUE
             OPEN (23,FILE='TEMP23.TXT',STATUS='NEW')
             L=0
             DO 100 K=1,7
                LARGE=10000.0
                DO 110 J=1,7
                   IF (K.EQ.1) GOTO 96
                   REWIND 23
                   IF (K.EQ.2) THEN
                       READ (23,*) M(1)
```

```
                     IF (J.EQ.M(1)) GOTO 110
                     IF (J.NE.M(1)) GOTO 96
                 ENDIF
                 DO 95 I=1,K-1
                    READ (23,*,END=96) M(I)
                    IF ((J.EQ.7).AND.(M(I).EQ.7)) GOTO 95
                    IF (J.EQ.M(I)) GOTO 110
 95              CONTINUE
 96              DISTA(K,J)=((XP(K,FNO)-X(J,FNO))**2.+(YP(K,FNO)-Y(J,
   1                          FNO))**2.)**(1./2.)
                 IF (J.EQ.1) LARGE=10000.0
                 IF (DISTA(K,J).LT.LARGE) THEN
                     LARGE=DISTA(K,J)
                     N=J
                 ELSE
                     LARGE=LARGE
                 ENDIF
110           CONTINUE
              L=L+1
              M(L)=N
              WRITE (23,*) M(L)
              XN2(K,FNO)=X(N,FNO)
              YN2(K,FNO)=Y(N,FNO)
              WRITE (45,*) XN2(K,FNO),YN2(K,FNO)
100        CONTINUE
 85 CONTINUE
    REWIND 23
    DO 150 I=1,7
       READ (23,*,END=151) M(I)
150 CONTINUE
151 CALL PEXIT
    STOP
    END
```

```
      SUBROUTINE MATINV(A,N)
      DIMENSION INDEX(11,3)
      REAL*8 A(11,11),DETERM,PIVOT
      EQUIVALENCE (IROW,JROW),(ICOLUM,JCOLUM),(AMAX,T,SWAP)
   10 DETERM=1.0
   15 DO 20 J=1,N
   18    INDEX(J,3)=0
   20 CONTINUE
   30 DO 550 I=1,N
   40    AMAX=0.0
   45    DO 105 J=1,N
            IF (INDEX(J,3)-1) 60,105,60
   60       DO 100 K=1,N
               IF (INDEX(K,3)-1) 80,100,715
   80          IF (AMAX-ABS(A(J,K))) 85,100,100
   85          IROW=J
   90          ICOLUM=K
               AMAX=ABS(A(J,K))
  100       CONTINUE
  105    CONTINUE
         INDEX(ICOLUM,3)=INDEX(ICOLUM,3)+1
  260    INDEX(I,1)=IROW
  270    INDEX(I,2)=ICOLUM
  130    IF (IROW-ICOLUM) 140,310,140
  140    DETERM=-DETERM
  150    DO 200 L=1,N
  160       SWAP=A(IROW,L)
  170       A(IROW,L)=A(ICOLUM,L)
  180       A(ICOLUM,L)=SWAP
  200    CONTINUE
  310    PIVOT=A(ICOLUM,ICOLUM)
         DETERM=DETERM*PIVOT
  330    A(ICOLUM,ICOLUM)=1.0
  340    DO 350 L=1,N
            A(ICOLUM,L)=A(ICOLUM,L)/PIVOT
  350    CONTINUE
         DO 550 L1=1,N
            IF(L1-ICOLUM) 400,550,400
  400       T=A(L1,ICOLUM)
  420       A(L1,ICOLUM)=0.0
  430       DO 450 L=1,N
               A(L1,L)=A(L1,L)-A(ICOLUM,L)*T
  450       CONTINUE
  550 CONTINUE
  600 DO 710 I=1,N
  610    L=N+1-I
  620    IF (INDEX(L,1)-INDEX(L,2)) 630,710,630
  630    JROW=INDEX(L,1)
  640    JCOLUM=INDEX(L,2)
  650    DO 705 K=1,N
  660       SWAP=A(K,JROW)
  670       A(K,JROW)=A(K,JCOLUM)
  700       A(K,JCOLUM)=SWAP
  705    CONTINUE
  710 CONTINUE
      DO 730 K=1,N
         IF (INDEX(K,3)-1) 715,730,715
  730 CONTINUE
      GOTO 740
  715 WRITE (*,'(A)') ' MATRIX IS SINGULAR '
  740 RETURN
      END
```

```
     SUBROUTINE MATINV0(A,N)
     DIMENSION INDEX(3,3)
     REAL*8 A(3,3),DETERM,PIVOT
     EQUIVALENCE (IROW,JROW),(ICOLUM,JCOLUM),(AMAX,T,SWAP)
  10 DETERM=1.0
  15 DO 20 J=1,N
  18    INDEX(J,3)=0
  20 CONTINUE
  30 DO 550 I=1,N
  40    AMAX=0.0
  45    DO 105 J=1,N
           IF (INDEX(J,3)-1) 60,105,60
  60       DO 100 K=1,N
              IF (INDEX(K,3)-1) 80,100,715
  80          IF (AMAX-ABS(A(J,K))) 85,100,100
  85          IROW=J
  90          ICOLUM=K
              AMAX=ABS(A(J,K))
 100       CONTINUE
 105    CONTINUE
        INDEX(ICOLUM,3)=INDEX(ICOLUM,3)+1
 260    INDEX(I,1)=IROW
 270    INDEX(I,2)=ICOLUM
 130    IF (IROW-ICOLUM) 140,310,140
 140    DETERM=-DETERM
 150    DO 200 L=1,N
 160       SWAP=A(IROW,L)
 170       A(IROW,L)=A(ICOLUM,L)
 180       A(ICOLUM,L)=SWAP
 200    CONTINUE
 310    PIVOT=A(ICOLUM,ICOLUM)
        DETERM=DETERM*PIVOT
 330    A(ICOLUM,ICOLUM)=1.0
 340    DO 350 L=1,N
           A(ICOLUM,L)=A(ICOLUM,L)/PIVOT
 350    CONTINUE
        DO 550 L1=1,N
           IF(L1-ICOLUM) 400,550,400
 400       T=A(L1,ICOLUM)
 420       A(L1,ICOLUM)=0.0
 430       DO 450 L=1,N
              A(L1,L)=A(L1,L)-A(ICOLUM,L)*T
 450       CONTINUE
 550 CONTINUE
 600 DO 710 I=1,N
 610    L=N+1-I
 620    IF (INDEX(L,1)-INDEX(L,2)) 630,710,630
 630    JROW=INDEX(L,1)
 640    JCOLUM=INDEX(L,2)
 650    DO 705 K=1,N
 660       SWAP=A(K,JROW)
 670       A(K,JROW)=A(K,JCOLUM)
 700       A(K,JCOLUM)=SWAP
 705    CONTINUE
 710 CONTINUE
     DO 730 K=1,N
        IF (INDEX(K,3)-1) 715,730,715
 730 CONTINUE
     GOTO 740
 715 WRITE (*,'(A)') ' MATRIX IS SINGULAR '
 740 RETURN
     END
```

```
      PROGRAM TDC CALCULATION
$INCLUDE:'FORINTF.H'
$INCLUDE:'SUB4.FOR'
$DEBUG
$LARGE
C
C INITIALIZATION
C
      INTEGER*2 ROW,COL,POSN,JJ,P,FNO1,FNO2,FNO
      REAL*8 L1(11),L2(11),XN1(7,100),YN1(7,100),XN2(7,100),YN2(7,10
     1        0),B(4,3),C(4,1),D(3,4),SUM,F(3,4),G(3,1),A(3,3),E(3,3)
     1        ,X3(7,100),Y3(7,100),Z3(7,100),L
      DIMENSION INDEX(3,3)
C
C CREATING A NEW FILE FOR THREE DIMENTIONAL COORDINATES OF MARKER
C
      OPEN(10,FILE='TDC.TXT',STATUS='NEW')
C
C READING CALIBRATION PARAMETERS OF TWO CAMERAS
C
      OPEN(5,FILE='CALIB1.TXT')
      OPEN(6,FILE='CALIB2.TXT')
      DO 10 I=1,11
          READ (5,*) L1(I)
   10 CONTINUE
      DO 15 I=1,11
          READ(6,*)L2(I)
   15 CONTINUE
C
C READING TWO DIMENTIONAL COORDINATES OF MARKERS
C
      OPEN(40,FILE='NOUT1.TXT')
      OPEN(45,FILE='NOUT2.TXT')
      FNO1=0
      DO 20 J=1,1000
          DO 22 I=1,7
              READ (40,*,END=4) XN1(I,J),YN1(I,J)
   22     CONTINUE
          FNO1=FNO1+1
   20 CONTINUE
    4 FNO2=0
      DO 25 J=1,1000
          DO 27 I=1,7
              READ (45,*,END=5) XN2(I,J),YN2(I,J)
   27     CONTINUE
          FNO2=FNO2+1
   25 CONTINUE
C
C CALCULATION OF THE ELEMENTS OF MATRIX [B] : [4 X 3]
C
C                                      T
C TRANSPOSE OF MATRIX [B] : [D]=[B]   : [3 X 4]
C
C CALCULATION OF THE THREE DIMENTIONAL COORDINATES OF MARKERS
C
    5 IF (FNO1.GT.FNO2)THEN
          FNO=FNO2
      ELSE
          FNO=FNO1
      ENDIF
```

```
C
C CREATING A DATA FILE FOR THE DISTANCE BETWEEN THE MARKERS NO. 5 AND 6
C
      OPEN (33,FILE='DIST.TXT',STATUS='NEW')
C
      DO 30 J=1,FNO
          DO 40 I=1,7
              B(1,1)=L1(1)-L1(9)*XN1(I,J)
              D(1,1)=B(1,1)
              B(1,2)=L1(2)-L1(10)*XN1(I,J)
              D(2,1)=B(1,2)
              B(1,3)=L1(3)-L1(11)*XN1(I,J)
              D(3,1)=B(1,3)
              B(2,1)=L1(5)-L1(9)*YN1(I,J)
              D(1,2)=B(2,1)
              B(2,2)=L1(6)-L1(10)*YN1(I,J)
              D(2,2)=B(2,2)
              B(2,3)=L1(7)-L1(11)*YN1(I,J)
              D(3,2)=B(2,3)
C
              B(3,1)=L2(1)-L2(9)*XN2(I,J)
              D(1,3)=B(3,1)
              B(3,2)=L2(2)-L2(10)*XN2(I,J)
              D(2,3)=B(3,2)
              B(3,3)=L2(3)-L2(11)*XN2(I,J)
              D(3,3)=B(3,3)
              B(4,1)=L2(5)-L2(9)*YN2(I,J)
              D(1,4)=B(4,1)
              B(4,2)=L2(6)-L2(10)*YN2(I,J)
              D(2,4)=B(4,2)
              B(4,3)=L2(7)-L2(11)*YN2(I,J)
              D(3,4)=B(4,3)
C
C CALCULATION OF THE ELEMENTS OF MATRIX [C] : [4 X 1]
C
              C(1,1)=XN1(I,J)-L1(4)
              C(2,1)=YN1(I,J)-L1(8)
C
              C(3,1)=XN2(I,J)-L2(4)
              C(4,1)=YN2(I,J)-L2(8)
C                                T
C MATRIX MULTIPLICATION : [A]=[B] [B] : [3 X 3]
C
              DO 70 ROW=1,3
                  DO 80 COL=1,3
                      SUM=0.0
                      DO 90 POSN=1,4
                          SUM=SUM+D(ROW,POSN)*B(POSN,COL)
   90                 CONTINUE
                      A(ROW,COL)=SUM
   80             CONTINUE
   70         CONTINUE
C                             T     -1        -1
C MATRIX INVERSION : [E]={ [B] [B] }  ={ [A] }   : [3 X 3]
C
              N=3
              CALL MATINV0(A,N)
              DO 100 N=1,3
                 DO 110 M=1,3
                    E(M,N)=A(M,N)
  110            CONTINUE
  100         CONTINUE
C                                  T     -1   T
C MATRIX MULTIPLICATION : [F]={ [B] [B] }  [B]  : [3 X 4]
C PSEUDO-INVERSE MATRIX CALCULATION
C
```

```
              DO 130 ROW=1,3
                  DO 140 COL=1,4
                      SUM=0.0
                      DO 150 POSN=1,3
                          SUM=SUM+E(ROW,POSN)*D(POSN,COL)
  150                 CONTINUE
                      F(ROW,COL)=SUM
  140             CONTINUE
  130             CONTINUE
C                                  T     -1  T
C MATRIX MULTIPLICATION : [G]=( [B] [B] ) [B] [C] : [3 X 1]
C THREE DIMENTIONAL COORDINATES OF MARKER : X Y Z
C
              DO 160 ROW=1,3
                      SUM=0.0
                      DO 180 POSN=1,4
                          SUM=SUM+F(ROW,POSN)*C(POSN,1)
  180                 CONTINUE
                      G(ROW,1)=SUM
  160         CONTINUE
C
C THREE DIMENTIONAL COORDINATES OF MARKER
C
              X3(I,J)=G(1,1)
              Y3(I,J)=G(2,1)
              Z3(I,J)=G(3,1)
C
              WRITE(10,*)X3(I,J),Y3(I,J),Z3(I,J)
C
              IF (I.EQ.6) THEN
                  L=((X3(6,J)-X3(5,J))**2.+(Y3(6,J)-Y3(5,J))**2.+(Z3(6,
     1               J)-Z3(5,J))**2.)**(1./2.)
                  WRITE(33,*) L
              ENDIF
C
   40     CONTINUE
   30 CONTINUE
      CALL PEXIT
      STOP
      END
```

```
      PROGRAM CALCULATION OF EULER ANGLES
$INCLUDE:'FORINTF.H'
$LARGE
$DEBUG
C
C INITIALIZATION
C
      INTEGER*2 FNO
      REAL  X3(7,1000),Y3(7,1000),Z3(7,1000),R12,B11,B12,B13,XM,YM,ZM,
     1      R13,C11,C12,C13,A11,A12,A13,R34,B21,B22,B23,A21,A22,A23,
     1      C21,C22,C23,R3M,B31,B32,B33,R4M,A31,A32,A33,C31,C32,C33,
     1      PSIS(100),PHIS(100),THES(100),D11,D112,D13,E11,E12,E13,
     1      F11,F12,F13,PSIE(100),PHIE(100),THEE(100),D21,D22,D23,
     1      E21,E22,E23,F21,F22,F23,PSIW(100),PHIW(100),THEW(100),
     1      THES1(100),PHIS1(100),PSIS1(100),PSIS2(100),THES11(100)
     1      ,PSIE2(100),THEE11(100),THEE1(100),PHIE1(100),PSIE1(100
     1      ),PSIW2(100),THEW11(100),THEW1(100),PHIW1(100),PSIW1(100
     1      ),R46,RM7,R56,R,A01,A02,A03,B01,B02,B03,C01,C02,C03,T0,T00,
     1      T000,D01,D02,D03,E01,E02,E03,F01,F02,F03,A1,A2,A3
C
C CREATING  NEW FILES FOR EULER ANGLES
C
      OPEN (15,FILE='EULER1.TXT',STATUS='NEW')
      OPEN (16,FILE='EULER2.TXT',STATUS='NEW')
      OPEN (17,FILE='EULER3.TXT',STATUS='NEW')
C
      OPEN (71,FILE='EULER10.TXT',STATUS='NEW')
      OPEN (72,FILE='EULER20.TXT',STATUS='NEW')
      OPEN (73,FILE='EULER30.TXT',STATUS='NEW')
C
C READING THREE DIMENTIONAL COORDINATES OF MARKERS FROM FILE='TDC.TXT'
C
      OPEN (10,FILE='TDC.TXT')
      FNO=0
      DO 10 N=1,1000
          DO 20 M=1,7
              READ (10,*,END=4) X3(M,N),Y3(M,N),Z3(M,N)
   20     CONTINUE
          FNO=FNO+1
   10 CONTINUE
    4 BACKSPACE 10
C
C CALCULATION OF UINT VECTORS OF BODY ROTATING AXES
C
C                           ^ ^ ^
C FIXED AXES UINT VECTORS : I,J,K
C                           ^ ^ ^
C BODY AXES UNIT VECTORS :  i,j,k
C
      DO 30 N=1,FNO
C                          ^         ^       ^      ^      T
C SHOULDER UNIT VECTOR : [ E0(N) ]=[ i0(N)   j0(N)  k0(N) ]
C                        ^         ^     ^     ^
C                        i0(N)=A01*I+A02*J+A03*K
C                        ^         ^     ^     ^
C                        j0(N)=B01*I+B02*J+B03*K
C                        ^         ^     ^     ^
C                        k0(N)=C01*I+C02*J+C03*K
C
          R12=((X3(1,N)-X3(2,N))**2.+(Y3(1,N)-Y3(2,N))**2.+(Z3(1,N)-
```

```
     1         Z3(2,N))**2.)**(1./2.)
      B01=(X3(1,N)-X3(2,N))/R12
      B02=(Y3(1,N)-Y3(2,N))/R12
      B03=(Z3(1,N)-Z3(2,N))/R12
      T0=(B01**2.+B02**2.+B03**2.)**(1./2.)
C
      A1=(Y3(1,N)-Y3(2,N))*(Z3(3,N)-Z3(2,N))-(Z3(1,N)-Z3(2,N))*
     1         (Y3(3,N)-Y3(2,N))
      A2=(Z3(1,N)-Z3(2,N))*(X3(3,N)-X3(2,N))-(X3(1,N)-X3(2,N))*
     1         (Z3(3,N)-Z3(2,N))
      A3=(X3(1,N)-X3(2,N))*(Y3(3,N)-Y3(2,N))-(Y3(1,N)-Y3(2,N))*
     1         (X3(3,N)-X3(2,N))
      R13=(A1**2.+A2**2.+A3**2.)**(1./2.)
      A01=A1/R13
      A02=A2/R13
      A03=A3/R13
      T00=(A01**2.+A02**2.+A03**2.)**(1./2.)
C
      C01=A02*B03-A03*B02
      C02=A03*B01-A01*B03
      C03=A01*B02-A02*B01
      T000=(C01**2.+C02**2.+C03**2.)**(1./2.)
C                           ^           ^       ^       ^      T
C ARM UINT VECTORS   : [ E1(N)  ]=[ i1(N)   j1(N)   k1(N)  ]
C                         ^      ^     ^     ^
C                         i1(N)=A11*I+A12*J+A13*K
C                         ^      ^     ^     ^
C                         j1(N)=B11*I+B12*J+B13*K
C                         ^      ^     ^     ^
C                         k1(N)=C11*I+C12*J+C13*K
C
C
      R34=((X3(3,N)-X3(4,N))**2.+(Y3(3,N)-Y3(4,N))**2.+(Z3(3,N)-
     1         Z3(4,N))**2.)**(1./2.)
      B11=(X3(3,N)-X3(4,N))/R34
      B12=(Y3(3,N)-Y3(4,N))/R34
      B13=(Z3(3,N)-Z3(4,N))/R34
      T1=(B11**2.+B12**2.+B13**2.)**(1./2.)
C
      XM=(2./3.)*X3(5,N)+(1./3.)*X3(6,N)
      YM=(2./3.)*Y3(5,N)+(1./3.)*Y3(6,N)
      ZM=(2./3.)*Z3(5,N)+(1./3.)*Z3(6,N)
      R3M=(((YM-Y3(4,N))*(Z3(3,N)-Z3(4,N))-(ZM-Z3(4,N))*
     1         (Y3(3,N)-Y3(4,N)))**2.+((ZM-Z3(4,N))*(X3(3,N)-X3(4,N))-
     1         (XM-X3(4,N))*(Z3(3,N)-Z3(4,N)))**2.+((XM-X3(4,N))*
     1         (Y3(3,N)-Y3(4,N))-(YM-Y3(4,N))*(X3(3,N)-X3(4,N)))**2.)
     1         **(1./2.)
      C11=((YM-Y3(4,N))*(Z3(3,N)-Z3(4,N))-(ZM-Z3(4,N))*
     1       (Y3(3,N)-Y3(4,N)))/R3M
      C12=((ZM-Z3(4,N))*(X3(3,N)-X3(4,N))-(XM-X3(4,N))*
     1       (Z3(3,N)-Z3(4,N)))/R3M
      C13=((XM-X3(4,N))*(Y3(3,N)-Y3(4,N))-(YM-Y3(4,N))*
     1       (X3(3,N)-X3(4,N)))/R3M
      T2=(C11**2.+C12**2.+C13**2.)**(1./2.)
C
      A11=B12*C13-B13*C12
      A12=B13*C11-B11*C13
      A13=B11*C12-B12*C11
      T3=(A11**2.+A12**2.+A13**2.)**(1./2.)
C                              ^           ^       ^       ^      T
C FOREARM UNIT VECTORS : [ E2(N)  ]=[ i2(N)   j2(N)   k2(N)  ]
C                            ^      ^     ^     ^
C                            i2(N)=A21*I+A22*J+A23*K
C                            ^      ^     ^     ^
C                            j2(N)=B21*I+B22*J+B23*K
C                            ^      ^     ^     ^
```

```
C                        k2(N)=C21*I+C22*J+C23*K
C
          R4M=((X3(4,N)-XM)**2.+(Y3(4,N)-YM)**2.+(Z3(4,N)-ZM)**2.)
     1       **(1./2.)
          B21=(X3(4,N)-XM)/R4M
          B22=(Y3(4,N)-YM)/R4M
          B23=(Z3(4,N)-ZM)/R4M
          P1=(B21**2.+B22**2.+B23**2.)**(1./2.)
C
          R46=(((Y3(6,N)-Y3(4,N))*(Z3(5,N)-Z3(4,N))-(Z3(6,N)-Z3(4,N))*
     1          (Y3(5,N)-Y3(4,N)))**2.+((Z3(6,N)-Z3(4,N))*(X3(5,N)-X3(4,
     1         N))-(X3(6,N)-X3(4,N))*(Z3(5,N)-Z3(4,N)))**2.+((X3(6,N)-
     1         X3(4,N))*(Y3(5,N)-Y3(4,N))-(Y3(6,N)-Y3(4,N))*(X3(5,N)-
     1         X3(4,N)))**2.)**(1./2.)
          A21=((Y3(6,N)-Y3(4,N))*(Z3(5,N)-Z3(4,N))-(Z3(6,N)-Z3(4,N))*
     1         (Y3(5,N)-Y3(4,N)))/R46
          A22=((Z3(6,N)-Z3(4,N))*(X3(5,N)-X3(4,N))-(X3(6,N)-X3(4,N))*
     1         (Z3(5,N)-Z3(4,N)))/R46
          A23=((X3(6,N)-X3(4,N))*(Y3(5,N)-Y3(4,N))-(Y3(6,N)-Y3(4,N))*
     1         (X3(5,N)-X3(4,N)))/R46
          P2=(A21**2.+A22**2.+A23**2.)**(1./2.)
C
          C21=A22*B23-A23*B22
          C22=A23*B21-A21*B23
          C23=A21*B22-A22*B21
          P3=(C21**2.+C22**2.+C23**2.)**(1./2.)
C                       ^          ^      ^       ^       T
C HAND UNIT VECTORS : [ E3(N)  ]=[ i3(N)  j3(N)   k3(N)  ]
C                     ^         ^     ^     ^
C                     i3(N)=A31*I+A32*J+A33*K
C                     ^         ^     ^     ^
C                     j3(N)=B31*I+B32*J+B33*K
C                     ^         ^     ^     ^
C                     k3(N)=C31*I+C32*J+C33*K
C
          RM7=((XM-X3(7,N))**2.+(YM-Y3(7,N))**2.+(ZM-Z3(7,N))**2.)
     1         **(1./2.)
          B31=(XM-X3(7,N))/RM7
          B32=(YM-Y3(7,N))/RM7
          B33=(ZM-Z3(7,N))/RM7
          Q1=(B31**2.+B32**2.+B33**2.)**(1./2.)
C
          R56=(((Y3(5,N)-Y3(7,N))*(Z3(6,N)-Z3(7,N))-(Z3(5,N)-Z3(7,N))*
     1        (Y3(6,N)-Y3(7,N)))**2.+((Z3(5,N)-Z3(7,N))*(X3(6,N)-X3(7,N)
     1       )-(X3(5,N)-X3(7,N))*(Z3(6,N)-Z3(7,N)))**2.+((X3(5,N)-X3(7,
     1        N))*(Y3(6,N)-Y3(7,N))-(Y3(5,N)-Y3(7,N))*(X3(6,N)-X3(7,N)
     1        ))**2.)**(1./2.)
          A31=((Y3(5,N)-Y3(7,N))*(Z3(6,N)-Z3(7,N))-(Z3(5,N)-Z3(7,N))*
     1         (Y3(6,N)-Y3(7,N)))/R56
          A32=((Z3(5,N)-Z3(7,N))*(X3(6,N)-X3(7,N))-(X3(5,N)-X3(7,N))*
     1         (Z3(6,N)-Z3(7,N)))/R56
          A33=((X3(5,N)-X3(7,N))*(Y3(6,N)-Y3(7,N))-(Y3(5,N)-Y3(7,N))*
     1         (X3(6,N)-X3(7,N)))/R56
          Q2=(A31**2.+A32**2.+A33**2.)**(1./2.)
C
          C31=A32*B33-A33*B32
          C32=A33*B31-A31*B33
          C33=A31*B32-A32*B31
          Q3=(C31**2.+C32**2.+C33**2.)**(1./2.)
C
C CONVERSION FACTOR : DEGREES/RADIANS
C
          R=180./3.1415927
C
C CALCULATION OF EULER ANGLES FOR SHOULDER : PHI-S,THETA-S,PSI-S
```

```
C TRANSFORMATION MATRIX FOR SHOULDER :
C                                       ^     ^  ^  ^  T
C                         FIXED AXES  [ E ]=[ I  J  K ]
C                                       ^                ^
C                                     [ E0(N) ]=[ T0 ] [ E ]
C                                       ^                ^
C                                     [ E1(N) ]=[ T1 ] [ E ]
C                                       ^                    -1  ^
C                                     [ E1(N) ]=[ T1 ] [ T0 ]  [ E0(N) ]
C                                          -1      T
C                ORTHOGONAL AXES :    [ T ]  =[ T ]
C                                                        -1
C                                     [ D0 ]=[ T1 ][ T0 ]
C
          D01=A11*A01+A12*A02+A13*A03
          D02=A11*B01+A12*B02+A13*B03
          D03=A11*C01+A12*C02+A13*C03
C
          E01=B11*A01+B12*A02+B13*A03
          E02=B11*B01+B12*B02+B13*B03
          E03=B11*C01+B12*C02+B13*C03
C
          F01=C11*A01+C12*A02+C13*A03
          F02=C11*B01+C12*B02+C13*B03
          F03=C11*C01+C12*C02+C13*C03
C
          PSIS2(N)=ATAN(-D03/F03)
          PSIS(N)=(ATAN(-D03/F03))*R
          PHIS(N)=(ATAN(-E01/E02))*R
          THES(N)=(ATAN((E03*COS(PSIS2(N)))/F03))*R
C
          THES11(N)=ASIN(E03)
          THES1(N)=THES11(N)*R
          PHIS1(N)=(ACOS(E02/COS(THES11(N))))*R
          PSIS1(N)=(ACOS(F03/COS(THES11(N))))*R
C
          IF (PHIS1(N).GT.90.) PHIS(N)=PHIS1(N)
          IF ((PHIS1(N).LT.90.).AND.(PHIS(N).LT.0.)) PHIS1(N)=PHIS(N)
          IF (PSIS1(N).GT.90.) PSIS(N)=PSIS1(N)
          IF ((PSIS1(N).LT.90.).AND.(PSIS(N).LT.0.)) PSIS1(N)=PSIS(N)
C
          WRITE (15,200) PHIS(N),THES(N),PSIS(N)
          WRITE (71,200) PHIS1(N),THES1(N),PSIS1(N)
  200     FORMAT(10X,3F14.2)
C
C CALCULATION OF EULER ANGLES FOR ELBOW : PHI-E,THETA-E,PSI-E
C
C TRANSFORMATION MATRIX FOR ELBOW :
C                                              ^           ^
C                                             [E1(N)]=[T1] [E]
C                                              ^           ^
C                                             [E2(N)]=[T2] [E]
C                                              ^                -1 ^
C                                             [E2(N)]=[T2] [T1]  [E1(N)]
C                                                -1     T
C             ORTHOGONAL AXES :               [T]  =[T]
C                                                            -1
C                                             [D1]=[T2] [T1]
C
          D11=A21*A11+A22*A12+A23*A13
          D12=A21*B11+A22*B12+A23*B13
          D13=A21*C11+A22*C12+A23*C13
C
          E11=B21*A11+B22*A12+B23*A13
          E12=B21*B11+B22*B12+B23*B13
          E13=B21*C11+B22*C12+B23*C13
```

```
C
          F11=C21*A11+C22*A12+C23*A13
          F12=C21*B11+C22*B12+C23*B13
          F13=C21*C11+C22*C12+C23*C13
C
          PSIE2(N)=ATAN(-D13/F13)
          PSIE(N)=(ATAN(-D13/F13))*R
          PHIE(N)=(ATAN(-E11/E12))*R
          THEE(N)=(ATAN((E13*COS(PSIE2(N)))/F13))*R
C
          THEE11(N)=ASIN(E13)
          THEE1(N)=THEE11(N)*R
          PHIE1(N)=(ACOS(E12/COS(THEE11(N))))*R
          PSIE1(N)=(ACOS(F13/COS(THEE11(N))))*R
C
          IF (PHIE1(N).GT.90.) PHIE(N)=PHIE1(N)
          IF ((PHIE1(N).LT.90.).AND.(PHIE(N).LT.0.)) PHIE1(N)=PHIE(N)
          IF (PSIE1(N).GT.90.) PSIE(N)=PSIE1(N)
          IF ((PSIE1(N).LT.90.).AND.(PSIE(N).LT.0.)) PSIE1(N)=PSIE(N)
C
          WRITE (16,200) PHIE(N),THEE(N),PSIE(N)
          WRITE (72,200) PHIE1(N),THEE1(N),PSIE1(N)
C
C CALCULATION OF EULER ANGLES FOR WRIST : PHI-W,THETA-W,PSI-W
C
C TRANSFORMATION MATRIX FOR WRIST :
C                                    ^              ^
C                                   [E2(N)] = [T2] [E]
C                                    ^              ^
C                                   [E3(N)] = [T3] [E]
C                                    ^                 -1 ^
C                                   [E3(N)] = [T3] [T2]  [E2(N)]
C                                       -1     T
C             ORTHOGONAL AXES :    [T2]  =[T2]
C                                                 T
C                                   [D2]=[T3] [T2]
C
          D21=A31*A21+A32*A22+A33*A23
          D22=A31*B21+A32*B22+A33*B23
          D23=A31*C21+A32*C22+A33*C23
          Q10=(D21**2.+D22**2.+D23**2.)**(1./2.)
C
          E21=B31*A21+B32*A22+B33*A23
          E22=B31*B21+B32*B22+B33*B23
          E23=B31*C21+B32*C22+B33*C23
          Q20=(E21**2.+E22**2.+E23**2.)**(1./2.)
C
          F21=C31*A21+C32*A22+C33*A23
          F22=C31*B21+C32*B22+C33*B23
          F23=C31*C21+C32*C22+C33*C23
          Q30=(F21**2.+F22**2.+F23**2.)**(1./2.)
C
          PSIW2(N)=ATAN(-D23/F23)
          PSIW(N)=(ATAN(-D23/F23))*R
          PHIW(N)=(ATAN(-E21/E22))*R
          THEW(N)=(ATAN((E23*COS(PSIW2(N)))/F23))*R
C
          THEW11(N)=ASIN(E23)
          THEW1(N)=THEW11(N)*R
          PHIW1(N)=(ACOS(E22/COS(THEW11(N))))*R
          V=F23/COS(THEW11(N))
          IF (V.GT.1.) THEN
              V=1.0
          ENDIF
          PSIW1(N)=(ACOS(V))*R
C
```

```
          IF (PHIW1(N).GT.90.) PHIW(N)=PHIW1(N)
          IF ((PHIW1(N).LT.90.).AND.(PHIW(N).LT.0.)) PHIW1(N)=PHIW(N)
          IF (PSIW1(N).GT.90.) PSIW(N)=PSIW1(N)
          IF ((PSIW1(N).LT.90.).AND.(PSIW(N).LT.0.)) PSIW1(N)=PSIW(N)
C
          WRITE (17,200) PHIW(N),THEW(N),PSIW(N)
          WRITE (73,200) PHIW1(N),THEW1(N),PSIW1(N)
C
   30 CONTINUE
      CALL PEXIT
      STOP
      END
```

```
      PROGRAM STICK DIAGRAM PLOTTING IN XY PLANE
$INCLUDE:'FORINTF.H'
$LARGE
C
C INITIALIZATION
C
      REAL XN1(7,100),YN1(7,100),ZN1(7,100)
      INTEGER*2 X(6,100),Y(6,100),M,N,FNO
C
C READING THREE DIMENTIONAL COORDINATES FROM FILE : TDC.TXT
C
      OPEN(10,FILE='TDC.TXT')
      OPEN (92,FILE='TEMP92.TXT',STATUS='NEW')
      FNO=0
      DO 10 J=1,100
          L=1
          DO 20 I=1,7
              READ(10,*,END=4) XN1(I,J),YN1(I,J),ZN1(I,J)
              IF (I.EQ.5) GOTO 20
              IF (I.EQ.6) THEN
                  XN1(L,J)=(8./11.)*XN1(5,J)+(3./11.)*XN1(6,J)
                  YN1(L,J)=(8./11.)*YN1(5,J)+(3./11.)*YN1(6,J)
                  GOTO 100
              ENDIF
              XN1(L,J)=XN1(I,J)
              YN1(L,J)=YN1(I,J)
  100         P=XN1(L,J)*470
              M=INT(P)-150
              X(L,J)=512-M
              Q=YN1(L,J)*470
              N=INT(Q)-250
              Y(L,J)=N
              WRITE (92,*) X(L,J),Y(L,J)
              L=L+1
   20     CONTINUE
          FNO=FNO+1
   10 CONTINUE
C
C INITIALIZING THE BOARD
C CLEARING THE SCREEN TO INDEX 255
C SET THE INDEX TO 0 FOR PLOTING
C
    4 I=INIT(620)
      CALL SETIND(255)
      CALL CLEAR(0,7)
      CALL SETIND(0)
C
C PLOTING STICK DIAGRAM FOR TWO DIMENTIONAL IMAGES
C NOTE THAT THE IMAGE PLANE IS NOT PARALLEL TO XY,XZ,AND YZ PLANES
C
      WRITE(*,*) FNO
      REWIND 92
      DO 30 J=1,FNO
          DO 40 I=1,6
              READ (92,*) X(I,J),Y(I,J)
              IF (I.LT.3) GOTO 40
              IF (I.EQ.3) THEN
                  CALL MOVETO (X(I,J),Y(I,J))
              ENDIF
              IF (I.GT.3) THEN
```

```
                 CALL LINETO (X(I,J),Y(I,J))
              ENDIF
40         CONTINUE
30    CONTINUE
      CALL PEXIT
      STOP
      END
```

```
      PROGRAM STICK DIAGRAM PLOTTING IN ZY PLANE
$INCLUDE:'FORINTF.H'
$LARGE
C
C INITIALIZATION
C
      REAL XN1(7,100),YN1(7,100),ZN1(7,100)
      INTEGER*2 X(6,100),Y(6,100),M,N,FNO
C
C READING THREE DIMENTIONAL COORDINATES FROM FILE : TDC.TXT
C
      OPEN(10,FILE='TDC.TXT')
      OPEN (93,FILE='TEMP93.TXT',STATUS='NEW')
      FNO=0
      DO 10 J=1,100
          L=1
          DO 20 I=1,7
              READ(10,*,END=4) XN1(I,J),YN1(I,J),ZN1(I,J)
              IF (I.EQ.5) GOTO 20
              IF (I.EQ.6) THEN
                  YN1(L,J)=(8./11.)*YN1(5,J)+(3./11.)*YN1(6,J)
                  ZN1(L,J)=(8./11.)*ZN1(5,J)+(3./11.)*ZN1(6,J)
                  GOTO 100
              ENDIF
              YN1(L,J)=YN1(I,J)
              ZN1(L,J)=ZN1(I,J)
  100         P=ZN1(L,J)*470
              M=INT(P)
              Y(L,J)=477-M
              Q=YN1(L,J)*470
              N=INT(Q)-250
              X(L,J)=N
              WRITE (93,*) X(L,J),Y(L,J)
              L=L+1
   20     CONTINUE
          FNO=FNO+1
   10 CONTINUE
C
C PLOTTING STICK DIAGRAM FOR TWO DIMENTIONAL IMAGES
C NOTE THAT THE IMAGE PLANE IS NOT PARALLEL TO XY,XZ,AND YZ PLANES
C
    4 WRITE(*,*) FNO
      REWIND 93
      DO 30 J=1,FNO
          DO 40 I=1,6
              READ (93,*) X(I,J),Y(I,J)
              IF (I.LT.3) GOTO 40
              IF (I.EQ.3) THEN
                  CALL MOVETO (X(I,J),Y(I,J))
              ENDIF
              IF (I.GT.3) THEN
                  CALL LINETO (X(I,J),Y(I,J))
              ENDIF
   40     CONTINUE
   30 CONTINUE
      CALL PEXIT
      STOP
      END
```

```
      PROGRAM STICK DIAGRAM PLOTTING IN XZ PLANE
$INCLUDE:'FORINTF.H'
$LARGE
C
C INITIALIZATION
C
      REAL XN1(7,100),YN1(7,100),ZN1(7,100)
      INTEGER*2 X(6,100),Y(6,100),M,N,FNO
C
C READING THREE DIMENTIONAL COORDINATES FROM FILE : TDC.TXT
C
      OPEN(10,FILE='TDC.TXT')
      OPEN(94,FILE='TEMP94.TXT',STATUS='NEW')
      FNO=0
      DO 10 J=1,100
          L=1
          DO 20 I=1,7
              READ (10,*,END=4) XN1(I,J),YN1(I,J),ZN1(I,J)
              IF (I.EQ.5) GOTO 20
              IF (I.EQ.6) THEN
                  XN1(L,J)=(8./11.)*XN1(5,J)+(3./11.)*XN1(6,J)
                  ZN1(L,J)=(8./11.)*ZN1(5,J)+(3./11.)*ZN1(6,J)
                  GOTO 100
              ENDIF
              XN1(L,J)=XN1(I,J)
              ZN1(L,J)=ZN1(I,J)
  100         P=XN1(L,J)*470
              M=INT(P)-150
              X(L,J)=512-M
              Q=ZN1(L,J)*470
              N=INT(Q)
              Y(L,J)=477-N
              WRITE (94,*) X(L,J),Y(L,J)
              L=L+1
   20     CONTINUE
          FNO=FNO+1
   10 CONTINUE
C
C PLOTTING STICK DIAGRAM FOR TWO DIMENTIONAL IMAGES
C NOTE THAT THE IMAGE PLANE IS NOT PARALLEL TO XY,XZ,AND YZ PLANES
C
    4 WRITE(*,*) FNO
      REWIND 94
      DO 30 J=1,FNO
          DO 40 I=1,6
              READ (94,*) X(I,J),Y(I,J)
              IF (I.LT.3) GOTO 40
              IF (I.EQ.3) THEN
                  CALL MOVETO (X(I,J),Y(I,J))
              ENDIF
              IF (I.GT.3) THEN
                  CALL LINETO (X(I,J),Y(I,J))
              ENDIF
   40     CONTINUE
   30 CONTINUE
      CALL PEXIT
      STOP
      END
```

B. Hardware Component technical specifications

Hardware Component Technical Specifications

(1) TV Camera:

Panasonic, Model WV-CD20 (B & W)
510(H) x 492 (V) Elment CCD Type
Internal or external sync.
Scanning: 521 Lines/60 Fields/30Frames
H: 15.734 K Hz
V: 59.9 Hz
Resolution: H: 380 lines at center
V: 350 lines at center
Lens Mount: C-Mount

(2) Zoom Lens:

TV Zoom Lens
12.5 mm - 75 mm
1: 1.8
C - Mount

(3) VCR:

Sony, Model SL-HF 1000
Play back speed: freeze, 1/10, 1/5, normal
Tape counter: frame by frame counter
Adjustment: slow tacking adjustment
freeze picture adjustment

Sony, Model SL-700

Tape: Sony, Dynamicron PRO-X/L-250

(4) Video Light:

SAFARI, Model VS-650
Focusing video quartz light
Lamp type: DYH 120V/650W

(5) Monitor:

Sony, Model CVM-112 (B&W)
Video monitor
Picture tube 11"

(6) PC:

IBM-PC-XT compatible personal computer (Mind II)
640 K memory
8 mHz clock

(7) Video Digitiser Board:

Matrox PIP-1024A video-digitiser-fram buffer board
Runs under PIPEZ software

(8) Image Processing Monitor:

Sony Trinitron RGB color monitor with computer and RGB (image) channels

(9) Calibrating Frame:

18" x 26" x 38" steel frame with eight 1.5" table-tennis balls (calibration markers)

(10) Body Marker:

11/16" white sperical reflective markers

C. Detailed collected data

TABLE 1. EULER ANGLES - SHOULDER JOINT - DRINKING WITH A CUP.
(ANGLE : DEGREE , F : 1/30 SEC.)

EULER ANGLE	PHI			THETA			PSI			PERFORMANCE
SUBJECT	MIN.	MAX.	ARC	MIN.	MAX.	ARC	MIN.	MAX.	ARC	TIME (F)
1	11.11	29.80	18.69	-27.90	-33.60	5.70	0.13	10.57	10.44	85
2	9.92	21.52	11.60	-41.10	-54.88	13.78	-0.27	7.62	7.89	90
3	27.57	48.81	21.24	-27.54	-37.07	9.53	12.60	29.27	16.67	65
4	22.94	74.30	51.36	-38.07	-59.38	21.31	19.85	42.63	22.78	56
5	12.58	31.05	18.47	-28.57	-52.09	23.52	7.28	21.87	14.59	75
6	31.79	68.59	36.80	-24.05	-52.02	27.97	15.03	40.22	25.19	75
7	24.50	52.97	28.47	-19.95	-57.20	37.25	15.65	34.69	19.04	85
8	25.58	32.73	7.15	-39.09	-49.84	10.75	18.87	26.16	7.29	75
9	19.50	66.41	46.91	-36.36	-61.39	25.03	18.28	51.33	33.05	80
10	28.15	61.65	33.50	-27.71	-38.07	10.36	22.84	48.02	25.18	100
MEAN	21.36	48.78	27.42	-31.03	-49.55	18.52	13.03	31.23	18.21	78.6
S.D.	7.35	19.38	13.91	7.60	9.37	9.54	7.69	14.18	8.00	11.86

TABLE 2. EULER ANGLES - ELBOW JOINT - DRINKING WITH A CUP .
(ANGLE : DEGREE)

EULER ANGLE	PHI			THETA			PSI		
SUBJECT	MIN.	MAX.	ARC	MIN.	MAX.	ARC	MIN.	MAX.	ARC
1	87.61	143.11	55.50	-	-	-	27.61	3.28	30.89
2	76.60	136.12	59.52	-	-	-	26.72	-9.05	17.67
3	75.31	138.12	62.81	-	-	-	17.06	0.14	17.20
4	80.26	133.75	53.49	-	-	-	44.76	3.50	48.26
5	78.22	135.54	57.32	-	-	-	41.93	-8.00	33.93
6	71.72	135.83	64.11	-	-	-	31.19	-2.65	28.54
7	84.27	134.06	49.79	-	-	-	36.94	-5.93	31.01
8	77.93	137.21	59.28	-	-	-	26.52	-5.87	20.65
9	86.13	136.08	49.95	-	-	-	33.81	-5.00	28.81
10	64.65	129.41	64.76	-	-	-	13.85	6.79	20.64
MEAN	78.27	135.92	57.65	-	-	-	30.04	-2.28	27.76
S.D.	6.55	3.30	5.18	-	-	-	9.39	5.14	8.92

NOTE : PSI IN THIS TABLE IS DEFINED AS PSI (CALCULATED) - 90 ,THUS
PSI (MIN.) : SUPINATION
PSI (MAX.) : PRONATION

TABLE 3. EULER ANGLES – WRIST JOINT – DRINKING WITH A CUP .
(ANGLE : DEGREE)

EULER ANGLE	PHI			THETA			PSI		
SUBJECT	MIN.	MAX.	ARC	MIN.	MAX.	ARC	MIN.	MAX.	ARC
1	-0.96	-28.66	27.70	18.54	22.82	4.28	0.31	6.88	6.57
2	-1.69	-7.27	5.58	11.16	18.93	7.77	0.36	1.67	1.31
3	-0.90	-16.12	15.22	9.45	22.14	12.69	0.16	3.92	3.76
4	+4.68	-4.89	9.57	24.29	33.86	9.57	-1.21	1.30	2.51
5	0.93	-5.26	6.19	9.23	12.25	3.02	-0.12	0.58	0.70
6	-8.03	-19.43	11.40	6.69	9.54	2.85	2.00	3.75	1.75
7	-7.22	-20.13	12.91	14.76	20.98	6.22	1.56	4.15	2.59
8	-3.08	-14.77	11.69	4.41	10.42	6.01	0.39	1.76	1.37
9	-6.86	-20.48	13.62	10.84	23.74	12.90	1.56	3.29	1.73
10	-6.55	-26.89	20.34	2.02	14.39	12.37	1.02	3.07	2.05
MEAN	-2.97	-16.39	13.42	11.14	18.91	7.77	0.60	3.04	2.43
S.D.	3.94	8.02	6.25	6.29	7.08	3.73	0.90	1.73	1.59

TABLE 4. EULER ANGLES - SHOULDER JOINT - EATING WITH A FORK.
(ANGLE : DEGREE , F : 1/30 SEC.)

EULER ANGLE	PHI			THETA			PSI			PERFORMANCE
SUBJECT	MIN.	MAX.	ARC	MIN.	MAX.	ARC	MIN.	MAX.	ARC	TIME (F)
1	9.16	28.24	19.08	-16.36	-30.09	13.73	2.92	13.13	10.21	39
2	12.72	18.63	5.91	-37.18	-44.98	7.80	-4.04	5.17	9.21	70
3	19.33	48.37	29.04	-31.98	-39.76	7.78	15.28	30.13	14.85	55
4	24.03	60.27	36.24	-40.17	-50.95	10.78	27.42	41.54	14.12	36
5	4.35	22.66	18.31	-16.75	-26.78	10.03	8.05	21.78	13.73	85
6	19.67	45.11	25.44	-18.51	-31.42	12.91	16.71	30.59	13.88	75
7	17.23	47.99	30.76	-21.01	-34.73	13.72	9.64	25.49	15.85	55
8	19.57	35.11	15.54	-27.29	-38.83	11.54	16.00	31.24	15.24	40
9	14.67	42.92	28.25	-22.91	-33.43	10.52	2.82	14.88	12.06	65
10	22.12	57.70	35.58	-22.31	-38.64	16.33	34.38	45.23	10.85	65
MEAN	16.28	40.70	24.42	-25.45	-36.96	11.51	12.92	25.92	13.00	58.5
S.D.	5.79	13.44	9.10	8.02	6.89	2.58	11.06	11.91	2.16	15.63

TABLE 5. EULER ANGLES - ELBOW JOINT - EATING WITH A FORK.
(ANGLE : DEGREE)

EULER ANGLE	PHI			THETA			PSI		
SUBJECT	MIN.	MAX.	ARC	MIN.	MAX.	ARC	MIN.	MAX.	ARC
1	115.74	137.42	21.68	-	-	-	69.21	44.12	113.33
2	105.75	128.41	22.66	-	-	-	61.00	25.52	86.52
3	107.21	131.47	24.26	-	-	-	59.95	45.76	105.71
4	93.09	125.36	32.27	-	-	-	62.92	41.73	104.65
5	103.54	131.69	28.15	-	-	-	70.25	31.21	101.46
6	92.75	131.02	38.27	-	-	-	46.83	39.85	86.68
7	101.65	133.50	31.85	-	-	-	47.82	45.09	92.91
8	106.03	130.27	24.24	-	-	-	53.80	39.21	93.01
9	98.38	124.90	26.52	-	-	-	48.69	50.50	99.19
10	81.77	116.36	34.59	-	-	-	56.37	30.40	86.77
MEAN	100.59	129.04	28.45	-	-	-	57.68	39.34	97.02
S.D.	9.03	5.48	5.28	-	-	-	8.04	7.51	8.83

NOTE : PSI IN THIS TABLE IS DEFINED AS PSI (CALCULATED) - 90 ,THUS
PSI (MIN.) : SUPINATION
PSI (MAX.) : PRONATION

TABLE 6. EULER ANGLES - WRIST JOINT - EATING WITH A FORK.
(ANGLE : DEGREE)

EULER ANGLE	PHI			THETA			PSI		
SUBJECT	MIN.	MAX.	ARC	MIN.	MAX.	ARC	MIN.	MAX.	ARC
1	-22.66	-34.00	11.34	0.61	8.49	7.88	2.20	3.30	1.10
2	-4.69	-17.22	12.53	-2.35	8.36	10.71	0.54	2.59	2.05
3	-9.27	-24.75	15.48	0.46	9.50	9.04	0.76	3.12	2.36
4	-22.50	-39.11	16.61	14.75	27.98	13.23	2.94	9.55	6.61
5	-10.57	-28.01	17.44	-8.99	0.09	9.08	0.26	1.83	1.57
6	-18.72	-32.68	13.96	-10.89	-2.55	8.34	0.40	2.67	2.27
7	-26.42	-33.86	7.44	7.06	10.21	3.15	1.48	3.38	1.90
8	-11.10	-23.22	12.12	-7.56	-2.35	5.21	-0.01	0.31	0.32
9	-6.91	-21.45	14.54	3.37	13.25	9.88	0.68	2.60	1.92
10	-4.55	-26.94	22.39	-16.90	-12.99	3.91	-0.99	-0.08	0.91
MEAN	-13.74	-28.12	14.38	-2.04	6.00	8.04	0.83	2.93	2.10
S.D.	7.69	6.40	3.82	8.86	10.56	2.98	1.07	2.48	1.62

TABLE 7. EULER ANGLES - SHOULDER JOINT - EATING WITH A SPOON.
(ANGLE : DEGREE , F : 1/30 SEC.)

EULER ANGLE	PHI			THETA			PSI			PERFORMANCE
SUBJECT	MIN.	MAX.	ARC	MIN.	MAX.	ARC	MIN.	MAX.	ARC	TIME (F)
1	9.05	32.09	23.04	-21.28	-31.23	9.95	-2.96	9.50	12.46	80
2	1.12	9.97	8.85	-36.09	-48.92	12.83	-19.24	-3.07	16.17	90
3	22.24	46.77	24.53	-35.19	-43.79	8.60	22.00	26.70	4.70	55
4	17.16	59.90	42.74	-33.36	-53.50	20.14	21.30	43.63	22.33	65
5	-0.29	25.86	26.15	-24.06	-34.29	10.23	2.69	10.11	7.42	70
6	19.28	56.24	36.96	-9.71	-35.50	25.79	19.92	33.24	13.32	52
7	10.98	51.83	40.85	-23.25	-44.60	21.35	17.60	26.16	8.56	90
8	9.56	32.59	23.03	-26.87	-35.70	8.83	21.30	29.52	8.22	70
9	17.67	53.00	35.33	-14.44	-41.49	27.05	3.87	20.80	16.93	75
10	26.34	47.83	21.49	-25.52	-32.63	7.11	40.17	49.68	9.51	45
MEAN	13.31	41.61	28.30	-24.98	-40.16	15.19	12.66	24.63	11.96	69.2
S.D.	8.31	15.06	9.95	8.15	7.08	7.23	15.84	15.22	5.07	14.55

TABLE 8. EULER ANGLES - ELBOW JOINT - EATING WITH A SPOON.
(ANGLE : DEGREE)

EULER ANGLE	PHI			THETA			PSI		
SUBJECT	MIN.	MAX.	ARC	MIN.	MAX.	ARC	MIN.	MAX.	ARC
1	117.68	140.55	22.87	-	-	-	60.91	41.12	102.03
2	119.42	134.53	15.11	-	-	-	60.36	25.34	85.70
3	119.66	130.40	10.74	-	-	-	57.23	31.46	88.69
4	102.41	125.91	23.50	-	-	-	60.15	43.89	104.04
5	110.86	133.21	22.35	-	-	-	68.10	-6.61	61.49
6	90.72	132.70	41.98	-	-	-	45.52	4.89	50.41
7	113.29	133.72	20.43	-	-	-	52.51	38.08	90.59
8	110.76	131.01	20.25	-	-	-	59.13	19.47	78.60
9	105.31	121.91	16.60	-	-	-	55.07	39.15	94.22
10	89.14	115.47	26.33	-	-	-	56.72	3.34	60.06
MEAN	107.92	129.94	22.02	-	-	-	57.57	24.01	81.58
S.D.	10.47	6.76	7.94	-	-	-	5.63	17.10	17.54

NOTE : PSI IN THIS TABLE IS DEFINED AS PSI (CALCULATED) - 90 ,THUS
PSI (MIN.) : SUPINATION
PSI (MAX.) : PRONATION

TABLE 9. EULER ANGLES - WRIST JOINT - EATING WITH A SPOON.
(ANGLE : DEGREE)

EULER ANGLE	PHI			THETA			PSI		
SUBJECT	MIN.	MAX.	ARC	MIN.	MAX.	ARC	MIN.	MAX.	ARC
1	-22.22	-32.20	9.98	-0.81	7.96	8.77	1.60	4.56	2.96
2	-7.82	-25.28	17.46	3.30	13.16	9.86	1.27	4.47	3.20
3	-17.68	-28.07	10.39	-2.94	8.76	11.70	0.51	3.52	3.01
4	-18.30	-29.53	11.23	8.48	19.93	11.45	1.73	5.20	3.47
5	-13.45	-22.31	8.86	-12.52	-4.05	8.47	-1.19	0.00	1.19
6	-31.90	-42.63	10.73	-8.97	-3.29	5.68	-0.06	2.96	3.02
7	-24.29	-41.07	16.78	9.24	15.24	6.00	2.59	4.28	1.69
8	-21.42	-39.97	18.55	-6.03	5.25	11.28	0.12	2.75	2.63
9	-15.55	-22.06	6.51	10.02	14.77	4.75	1.89	3.32	1.43
10	-8.60	-25.73	17.13	-15.75	-7.53	8.22	-1.18	1.04	2.22
MEAN	-18.12	-30.88	12.76	-1.60	7.02	8.62	0.73	3.21	2.48
S.D.	6.94	7.38	4.06	8.80	8.83	2.38	1.23	1.55	0.76

TABLE 10. EULER ANGLES - SHOULDER JOINT - DRINKING WITH A CUP.
TAKING INITIAL DEVIATION INTO ACCOUNT
(ANGLE : DEGREE , F : 1/30 SEC.)

EULER ANGLE	PHI			THETA			PSI			PERFORMANCE
SUBJECT	MIN.	MAX.	ARC	MIN.	MAX.	ARC	MIN.	MAX.	ARC	TIME (F)
1	14.15	32.84	18.69	-13.56	-19.26	5.70	-3.87	6.57	10.44	85
2	7.28	18.88	11.60	-22.41	-36.19	13.78	6.72	14.61	7.89	90
3	23.81	45.05	21.24	-12.04	-21.57	9.53	11.08	27.75	16.67	65
4	19.98	71.34	51.36	-14.60	-35.91	21.31	10.65	33.43	22.78	56
5	11.66	30.13	18.47	-18.60	-42.12	23.52	1.24	15.83	14.59	75
6	15.59	52.39	36.80	1.18	-26.79	27.97	3.99	29.18	25.19	75
7	13.39	41.86	28.47	-1.67	-38.92	37.25	-11.07	7.97	19.04	85
8	17.30	24.45	7.15	-21.22	-31.97	10.75	15.60	22.89	7.29	75
9	18.63	65.54	46.91	-17.74	-42.77	25.03	14.96	48.01	33.05	80
10	16.43	49.93	33.50	-5.95	-16.31	10.36	2.74	27.92	25.18	100
MEAN	15.82	43.24	27.42	-12.66	-31.18	18.52	5.20	23.42	18.21	78.6
S.D.	4.37	16.27	13.91	7.69	9.15	9.54	8.00	11.98	8.00	11.86

TABLE 11. EULER ANGLES - ELBOW JOINT - DRINKING WITH A CUP .
TAKING INITIAL DEVIATION INTO ACCOUNT
(ANGLE : DEGREE)

EULER ANGLE	PHI			THETA			PSI		
SUBJECT	MIN.	MAX.	ARC	MIN.	MAX.	ARC	MIN.	MAX.	ARC
1	77.97	133.47	55.50	-	-	-	25.51	5.38	30.89
2	68.12	127.64	59.52	-	-	-	29.91	-12.24	17.67
3	62.55	125.36	62.81	-	-	-	22.25	-5.05	17.20
4	78.13	131.62	53.49	-	-	-	55.24	-6.98	48.26
5	72.11	129.43	57.32	-	-	-	28.25	5.68	33.93
6	63.80	127.91	64.11	-	-	-	37.70	-9.16	28.54
7	78.51	128.30	49.79	-	-	-	36.32	-5.31	31.01
8	67.96	127.24	59.28	-	-	-	29.76	-9.11	20.65
9	77.87	127.82	49.95	-	-	-	36.28	-7.47	28.81
10	68.22	132.98	64.76	-	-	-	10.42	10.22	20.64
MEAN	71.52	129.18	57.65	-	-	-	31.16	-3.40	27.76
S.D.	5.92	2.53	5.18	-	-	-	11.09	7.24	8.92

NOTE : PSI IN THIS TABLE IS DEFINED AS PSI (CALCULATED) - 90 ,THUS
PSI (MIN.) : SUPINATION
PSI (MAX.) : PRONATION

TABLE 12. EULER ANGLES - WRIST JOINT - DRINKING WITH A CUP .
TAKING INITIAL DEVIATION INTO ACCOUNT
(ANGLE : DEGREE)

EULER ANGLE	PHI			THETA			PSI		
SUBJECT	MIN.	MAX.	ARC	MIN.	MAX.	ARC	MIN.	MAX.	ARC
1	5.10	-22.60	27.70	17.00	21.28	4.28	-0.42	6.15	6.57
2	3.03	-2.55	5.58	7.93	15.70	7.77	-0.32	0.99	1.31
3	5.12	-10.10	15.22	4.30	16.99	12.69	-0.57	3.19	3.76
4	19.32	9.75	9.57	18.79	28.36	9.57	-2.77	-0.26	2.51
5	2.30	-3.89	6.19	12.09	15.11	3.02	-0.18	0.52	0.70
6	4.09	-7.31	11.40	1.19	4.04	2.85	-0.11	1.64	1.75
7	16.69	3.78	12.91	8.51	14.73	6.22	-0.65	1.94	2.59
8	0.60	-11.09	11.69	-0.57	5.44	6.01	-0.03	1.34	1.37
9	6.34	-7.28	13.62	1.84	14.74	12.90	-0.20	1.53	1.73
10	12.47	-7.87	20.34	12.24	24.61	12.37	0.66	2.71	2.05
MEAN	7.51	-5.92	13.42	8.33	16.10	7.77	-0.46	1.98	2.43
S.D.	6.06	8.28	6.25	6.35	7.17	3.73	0.84	1.68	1.59

TABLE 13. EULER ANGLES - SHOULDER JOINT - EATING WITH A FORK.
TAKING INITIAL DEVIATION INTO ACCOUNT
(ANGLE : DEGREE , F : 1/30 SEC.)

EULER ANGLE	PHI			THETA			PSI			PERFORMANCE
SUBJECT	MIN.	MAX.	ARC	MIN.	MAX.	ARC	MIN.	MAX.	ARC	TIME (F)
1	12.20	31.28	19.08	-2.02	-15.75	13.73	-1.08	9.13	10.21	39
2	10.08	15.99	5.91	-18.49	-26.29	7.80	2.95	12.16	9.21	70
3	15.57	44.61	29.04	-16.48	-24.26	7.78	13.76	28.61	14.85	55
4	21.07	57.31	36.24	-16.70	-27.48	10.78	18.22	32.34	14.12	36
5	3.43	21.74	18.31	-6.78	-16.81	10.03	2.01	15.74	13.73	85
6	3.47	28.91	25.44	6.72	-6.19	12.91	5.67	19.55	13.88	75
7	6.12	36.88	30.76	-2.73	-16.45	13.72	-17.08	-1.23	15.85	55
8	11.29	26.83	15.54	-9.42	-20.96	11.54	12.73	27.97	15.24	40
9	13.80	42.05	28.25	-4.29	-14.81	10.52	-0.50	11.56	12.06	65
10	10.40	45.98	35.58	-0.55	-16.88	16.33	14.28	25.13	10.85	65
MEAN	10.74	35.16	24.42	-7.07	-18.59	11.51	5.10	18.10	13.00	58.5
S.D.	5.20	11.91	9.10	7.76	6.02	2.58	9.83	10.00	2.16	15.63

TABLE 14. EULER ANGLES - ELBOW JOINT - EATING WITH A FORK.
TAKING INITIAL DEVIATION INTO ACCOUNT
(ANGLE : DEGREE)

EULER ANGLE	PHI			THETA			PSI		
SUBJECT	MIN.	MAX.	ARC	MIN.	MAX.	ARC	MIN.	MAX.	ARC
1	106.10	127.78	21.68	-	-	-	67.11	46.22	113.33
2	97.27	119.93	22.66	-	-	-	64.19	22.33	86.52
3	94.45	118.71	24.26	-	-	-	65.14	40.57	105.71
4	90.96	123.23	32.27	-	-	-	73.40	31.25	104.65
5	97.43	125.58	28.15	-	-	-	56.57	44.89	101.46
6	84.83	123.10	38.27	-	-	-	53.34	33.34	86.68
7	95.89	127.74	31.85	-	-	-	47.20	45.71	92.91
8	96.06	120.30	24.24	-	-	-	57.04	35.97	93.01
9	90.12	116.64	26.52	-	-	-	51.16	48.03	99.19
10	85.34	119.93	34.59	-	-	-	52.94	33.83	86.77
MEAN	93.84	122.29	28.45	-	-	-	58.81	38.21	97.02
S.D.	6.00	3.63	5.28	-	-	-	7.85	7.85	8.83

NOTE : PSI IN THIS TABLE IS DEFINED AS PSI (CALCULATED) - 90 ,THUS
PSI (MIN.) : SUPINATION
PSI (MAX.) : PRONATION

TABLE 15. EULER ANGLES - WRIST JOINT - EATING WITH A FORK.
TAKING INITIAL DEVIATION INTO ACCOUNT
(ANGLE : DEGREE)

EULER ANGLE	PHI			THETA			PSI		
SUBJECT	MIN.	MAX.	ARC	MIN.	MAX.	ARC	MIN.	MAX.	ARC
1	-16.60	-27.94	11.34	-0.93	6.95	7.88	1.47	2.57	1.10
2	0.03	-12.50	12.53	-5.58	5.13	10.71	-0.14	1.91	2.05
3	-3.25	-18.73	15.48	-4.69	4.35	9.04	0.03	2.39	2.36
4	-7.86	-24.47	16.61	9.25	22.48	13.23	1.38	7.99	6.61
5	-9.20	-26.64	17.44	-6.13	2.95	9.08	0.20	1.77	1.57
6	-6.60	-20.56	13.96	-16.39	-8.05	8.34	-1.71	0.56	2.27
7	-2.51	-9.95	7.44	0.81	3.96	3.15	-0.73	1.17	1.90
8	-7.42	-19.54	12.12	-12.54	-7.33	5.21	-0.43	-0.11	0.32
9	6.29	-8.25	14.54	-5.63	4.25	9.88	-1.08	0.84	1.92
10	14.47	-7.92	22.39	-6.68	-2.77	3.91	-1.35	-0.44	0.91
MEAN	-3.26	-17.65	14.38	-4.85	3.19	8.04	-0.24	1.86	2.10
S.D.	8.24	7.18	3.82	6.67	8.16	2.98	1.01	2.25	1.62

TABLE 16. EULER ANGLES - SHOULDER JOINT - EATING WITH A SPOON.
TAKING INITIAL DEVIATION INTO ACCOUNT
(ANGLE : DEGREE , F : 1/30 SEC.)

EULER ANGLE	PHI			THETA			PSI			PERFORMANCE
SUBJECT	MIN.	MAX.	ARC	MIN.	MAX.	ARC	MIN.	MAX.	ARC	TIME (F)
1	12.09	35.13	23.04	-6.94	-16.89	9.95	-6.96	5.50	12.46	80
2	-1.52	7.33	8.85	-17.40	-30.23	12.83	-12.25	3.92	16.17	90
3	18.48	43.01	24.53	-19.69	-28.29	8.60	20.48	25.18	4.70	55
4	14.20	56.94	42.74	-9.89	-30.03	20.14	12.10	34.43	22.33	65
5	-1.21	24.94	26.15	-14.09	-24.32	10.23	-3.35	4.07	7.42	70
6	3.08	40.04	36.96	15.52	-10.27	25.79	8.88	22.20	13.32	52
7	-0.13	40.72	40.85	-4.97	-26.32	21.35	-9.12	-0.56	8.56	90
8	1.28	24.31	23.03	-9.00	-17.83	8.83	18.03	26.25	8.22	70
9	16.80	52.13	35.33	4.18	-22.87	27.05	0.55	17.48	16.93	75
10	14.62	36.11	21.49	-3.76	-10.87	7.11	20.07	29.58	9.51	45
MEAN	7.77	36.07	28.30	-6.60	-21.79	15.19	4.84	16.80	11.96	69.2
S.D.	7.72	13.67	9.95	9.88	7.08	7.23	11.96	11.92	5.07	14.55

TABLE 17. EULER ANGLES - ELBOW JOINT - EATING WITH A SPOON.
TAKING INITIAL DEVIATION INTO ACCOUNT
(ANGLE : DEGREE)

EULER ANGLE	PHI			THETA			PSI		
SUBJECT	MIN.	MAX.	ARC	MIN.	MAX.	ARC	MIN.	MAX.	ARC
1	108.04	130.91	22.87	-	-	-	58.81	43.22	102.03
2	110.94	126.05	15.11	-	-	-	63.55	22.15	85.70
3	106.90	117.64	10.74	-	-	-	62.42	26.27	88.69
4	100.28	123.78	23.50	-	-	-	70.63	33.41	104.04
5	104.75	127.10	22.35	-	-	-	54.42	7.07	61.49
6	82.80	124.78	41.98	-	-	-	52.03	-1.62	50.41
7	107.53	127.96	20.43	-	-	-	51.89	38.70	90.59
8	100.79	121.04	20.25	-	-	-	62.37	16.23	78.60
9	97.05	113.65	16.60	-	-	-	57.54	36.68	94.22
10	92.71	119.04	26.33	-	-	-	53.29	6.77	60.06
MEAN	101.18	123.20	22.02	-	-	-	58.70	22.89	81.58
S.D.	8.10	5.02	7.94	-	-	-	5.77	14.60	17.54

NOTE : PSI IN THIS TABLE IS DEFINED AS PSI (CALCULATED) - 90 ,THUS
PSI (MIN.) : SUPINATION
PSI (MAX.) : PRONATION

TABLE 18. EULER ANGLES - WRIST JOINT - EATING WITH A SPOON.
TAKING INITIAL DEVIATION INTO ACCOUNT
(ANGLE : DEGREE)

EULER ANGLE	PHI			THETA			PSI		
SUBJECT	MIN.	MAX.	ARC	MIN.	MAX.	ARC	MIN.	MAX.	ARC
1	-16.16	-26.14	9.98	-2.35	6.42	8.77	0.87	3.83	2.96
2	-3.10	-20.56	17.46	0.07	9.93	9.86	0.59	3.79	3.20
3	-11.66	-22.05	10.39	-8.09	3.61	11.70	-0.22	2.79	3.01
4	-3.66	-14.89	11.23	2.98	14.43	11.45	0.17	3.64	3.47
5	-12.08	-20.94	8.86	-9.66	-1.19	8.47	-1.25	-0.06	1.19
6	-19.78	-30.51	10.73	-14.47	-8.79	5.68	-2.17	0.85	3.02
7	-0.38	-17.16	16.78	2.99	8.99	6.00	0.38	2.07	1.69
8	-17.74	-36.29	18.55	-11.01	0.27	11.28	-0.30	2.33	2.63
9	-2.35	-8.86	6.51	1.02	5.77	4.75	0.13	1.56	1.43
10	10.42	-6.71	17.13	-5.53	2.69	8.22	-1.54	0.68	2.22
MEAN	-7.65	-20.41	12.76	-4.40	4.21	8.62	-0.33	2.15	2.48
S.D.	8.95	8.67	4.06	5.92	6.19	2.38	0.95	1.31	0.76