Design of a Line Crawling Robot with an Intelligent Hybrid Control System

by

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A Thesis Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements for the Degree of

Master of Science
in Electrical and Computer Engineering

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THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES
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Abstract

This thesis presents the analysis, design, and simulation of a robot with an intelligent control system. The robot is designed to crawl on high voltage transmission lines and to carry payloads for inspection, diagnostics, and maintenance of components of the lines. Using the reconfigurable servo systems the robot, achieves the required mobility and explores the advantages of its various configurations as a result of its redundant multifunctional mechanical design. Many different maneuvers of the robot were introduced to make it possible to avoid and crawl around obstacles on the overhead lines. The hybrid behavior based control system with deliberative planning deals with unpredictable environment, working conditions and changing missions of the robot.

ACKNOWLEDGEMENTS

I would like to thanks my advisor Dr. J. F. Peters for his generous help, valuable advice, and support in my work on this thesis.

I also would like to thank Manitoba Hydro for supporting this research.

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1 Introduction

We live in a society that is extremely dependent on electrical sources of energy. Providing heat, light, and being the driving force of industry, electricity becomes an essential means for existence and sustainable growth of modern society. Thousands of kilometres of power transmission lines deliver electricity from power generating stations to customers in different geographic regions. A reliable supply of the electricity depends on the consistency the transmission through the power lines. In order to offer the required reliability of the transmission of electricity, network owners must provide periodic inspection, maintenance, and if required, repair of the lines and line equipment. Extended distances of the transmission lines require extensive and expensive methods of inspection and evaluation of the condition of the lines. There are numerous methods used for inspection and live maintenance of the transmission lines by the power companies, including helicopters or small planes (see [Mize93], [Fern02], [Buch87]). Power companies must provide for the safety of personal during the inspection and the maintenance work on live power transmission lines. High voltage and electric fields create hazardous conditions for workers while working at a close distance to the live line. There are applications, which use remote-operated robotic systems for the live line maintenance (see [Sawa92], [Mont03], [Tsun98], [Udod98]). The most promising applications involve the autonomous robotic systems, which can operate in remote locations for long periods of time. The robots perform light repair work, and continuous inspections of the power lines (see [Sawa92], [Mont03]).

Hydro Quebec LineROVer was initially designed for an overhead ground wire de-icing applications (see [Mont03]). This robot is equipped with a wheeled system that allows it to move along the wires. The robot has a set of replaceable payloads for performing inspections of the transmission lines such as "visual and infrared inspections, assessing conductor corrosion, and evaluating the conduction of compression splices" [Mont03]. The LineROVer can also replace an "overhead ground wire and insulator strings" [Mont03] and de-ice wires using an installed set of fixed steel blades. The robot can operate on one span only. This means that the robot cannot move from one span of the transmission line onto another one through the suspension clamps or dampers. Despite the robot's limited range of operation, the LineROVer has proven itself through good performance and was found to be extremely helpful.

Limitations of the range of operation of the robotic systems to only one span of the transmission line does not allow the use of overhead robots for remote applications because these robots need continuous presence of a maintenance team. The ability of the robot to pass across an obstacle on the line (e.g. suspension clams, insulator groups, compensators) becomes a necessary requirement for the autonomous robotic system meant to operate in remote areas. Tokyo Electric Power Inc. has developed one such a robotic system (see [Sawa92]). This robot carries different types of an inspection payloads and in comparison to the LineROVer has the ability to go around some obstacles and towers, but heavily relies on balance support from the side of a tower.

Another aspect, which contributes to capability of the robot to operate in remote areas, is the ability of control system to adjust itself for constantly changing environment and conditions of operation. The control system of the robot should provide the control of servo systems of functional components of the robot such as arms, wheeled drivers, or manipulators. The control system of the robot should also provide navigation of the robot on line, implementation of algorithms of recognition and bypassing obstacles, anticipation of unexpected situations on the line caused by weather, robot's malfunctions, or changes of mission plans. Thus, in addition to forming signals for the servo system, the control system of the robot should be able to analyze and recognize various situations on the line, and make decisions about the next robot's move. The class of control systems which are the best fitted for the mentioned tasks belongs to a class of behaviour based systems.

The concept of behaviours was developed by Brooks [Brok99] in a subsumption architecture and Arkin [Arki98] in a motor schema. Behaviour can be identified as a simple reaction to stimuli. Thus, behaviour describes response of the system to particular input information. Usually, the behaviour-based system consists of set of behaviours, which describes different responses of a system and involves different aspects of robot's activity. All behaviours work concurrently, preparing their own responses. When responses are ready, the system chooses the appropriate action by arbitrating the behaviours. There are different approaches for selection of an action. Thus, Brooks implements inhibition, or suppression, of low-level behaviours by high-level behaviours. Arkin introduces strength of stimulus and the final action is determined by a weighted summation of all behaviours. Another way of choosing the active behaviour from a set of behaviours is arbitrating according to the priorities of behaviours. Normally, the behaviours represent the reactive response of the system, which does not involve a high-level intelligence for forming the output of the system. For performing high-level planning the behaviour-based control systems use deliberative reasoning methods. The systems with the deliberative reasoning involve cognitive and learning algorithms for providing subgoals for lower level behaviours. The deliberative level of the control system use symbolic representation of the external and internal worlds of the robot, which can be incomplete in a highly dynamic environment. Thus, the reactive (or behaviour-based) systems provide fast response at expense of optimality and goal convergence, and deliberative level of the control systems provides goals and decisions which may have larger response time and can suffer precision. Our study of robotic control strategies has benefited from a number of related works which are dedicated to different aspects of behavioural control and deliberative reasoning (see e.g., [Brok99], [Arki98], [StAr01], [Park99], [LPet99], [Emer01], [Likh01]).

The objective of this thesis is to design a multipurpose autonomous robotic system, which will work on power transmission lines and will be used for the following purposes:

- line maintenance and light repair work on the lines
- inspection and diagnostics of elements of the lines such as insulators, conductors and line breakers
- de-icing of some critical elements of the lines

The functionality of the robot is provided by an intelligent hybrid control system, which sustain autonomous functioning of the robot. The multilayered structure of the control system reflects different aspects of the controls strategy of the robot such as guidance of the robot on the wire, reconfiguration of the robot and the control system according to the surrounding situation and needs of the robot, planning of the mission, servo control of functional components of the robot. The system combines feedback control, behaviour-based levels of control, and deliberative reasoning.

The design of the robot and its control system provides the ability of the device to bypass different types of obstacles allowing the robot to cross over and work continuously on different spans of transmission lines in remote areas without participation of the maintenance team.

The robot described in this thesis is considered intelligent because it has the ability to identify different obstacles and features of its environment, and to modify its behavior to permit it to accomplish its mission goals. A provision for planning by the robot is included in its current design. The robot planner makes it possible to cope with problems it encounters (e.g., bad weather conditions, failure in one of the robot's subsystems). So, for example, in the case where a subsystem (e.g., one of the legs) fails, the robot is designed to substitute an alternative behavior made possible by the presence of redundant architecture such as other legs or base extensions.

The design of the robot is presented in Chapter 1, where the detailed description of the robot is supported by examples of different types of motion and obstacle avoidance algorithms. This chapter outlines the functionality of the robot and its ability to perform different mission on the line. The architecture and design principles are considered in Chapter 2. Flexible and adaptable behavior based control system of the robot allows the robot to explore its reach functionality mentioned in the previous chapter. Chapter 3 is dedicated to the analysis, design and simulation of servo systems of the robot. Different configurations of the robot require different control strategies for the control system of the robot. These strategies are managed by the behavior based control system of the robot which is described in Chapter 4 and is concluded by a computer simulation of the obstacle avoidance maneuver of the robot. The outline of the work done is presented in Conclusion which includes a review of further directions of the research. The thesis includes an Appendix that presents control models and some parameters of the DC motors used for the design of the servo systems of the robot.

2 The Concept of Mechanical Design

Design of the robot begins with identification of technical requirements of the robot. These requirements reflect the knowledge of the environment where the robot should work, execute planned missions which should be accomplished by the robot, realize the reality of today's technology and available resources for designing the robot as well as take into account price/performance factor. All technical requirements can be divided into subcategories depending on the level of abstraction and the physical aspect of these requirements.

Analysis of missions and performed tasks

In order to accomplish the mission, the robot should posses the following functions:

- be able to carry and control a specific payload with a specific weight, size, power supply, and interface
- deliver a payload to a required location on the line with a reasonable speed, high maneuverability, and large service area
- provide control and co-operation with a payload
- provide long term autonomous functioning
- provide a robot-human interaction; communicate with a ground control station; receive commands; transmit data, and produce the adequate response

Analysis of working environment

The robot should work in a real environment which can be represented by the following factors:

- overhead lines of different profiles (e.g., diameters, length, and angle of inclination)
- different types of possible obstacles on the line (e.g., compensators, bypasses, insulators)
- harsh electro-magnetic environment
- uncertain and hostile weather conditions (e.g., temperature, wind, snow, ice, and lightning).

The following requirements reflect the impact of the environment on the design of the robot:

1. The robot should have an adaptive gripping system, which allows the robot to grasp, to hold, and to move along power lines with different profiles, shapes, sizes, including icy wires.
2. The robot should be able to perform obstacle-avoiding maneuvers in order to move from one section of the transmission line to another. The different types of maneuvers depend on the type of obstacles. This requires the robot to identify the shape and size of obstacles.
3. The robot that crawls along an energized line should have protections against electro-magnetic interference (EMI) from the line. Mechanical design of the robot should prevent the corona effect on the robot's body.
4. The robot should be resistant to wide ranges of temperatures.

5. The robot should be able to compensate for the impact of a wind. The wind may cause the robot to oscillate on the wire and can create the possibility of collision between the robot and elements of the transmission lines.

6. The robot should have a water proof design and a possibility of performing self-deicing.

Robot as a mobile object

The robot is a mobile object with the following requirements:

1. The robot should be able to work with limited power resources. This requires the robot to have highly efficient power supply sources, power management solutions, and power saving design.

2. The robot should be able to work with limited computational resources of on-board computers. This function requires the robot to have optimized algorithms, code, and effective computational architecture.

3. The robot has limitations of size and applied torques of servos, which require the robot to have optimal control solutions for servos.

4. The robot must have highly reliable mechanical systems and electrical systems.

5. The robot should have stable and effective control algorithms, which will provide adequate responses of the robot to a hostile and uncertain environment.

6. The robot should have effective navigational and sensor systems.

Available resources, environmental reality and expected functionality result sometimes in contradictory requirements. Thus, demands of sophisticated control capabilities may contradict the reality of limited computational resources, or the ability of the robot to carry the payload may be restricted by low-power servos. These demands dictate a design strategy in which the design of mechanical and electrical systems, control algorithms and software should be done concurrently. Only, by applying the system view on the problem is possible to obtain an optimal solution. Careful and detailed analysis of all possible trade-offs and implementation of alternative solutions can significantly reduce the complexity of the robot.

Finding solutions and building the robot that meets all the requirements is a primary goal of this thesis. Some assumptions were taken, such as:

- The overhead line is straight and without inclination.
- Only certain types of obstacles are chosen for consideration and simulation
- The effects of the EMI and corona phenomena from the power transmission lines are not considered since they require additional studies.

A robot designed to carry a diagnostic load and capable of performing different types of motion and avoiding obstacles is shown in Figure 2.1.

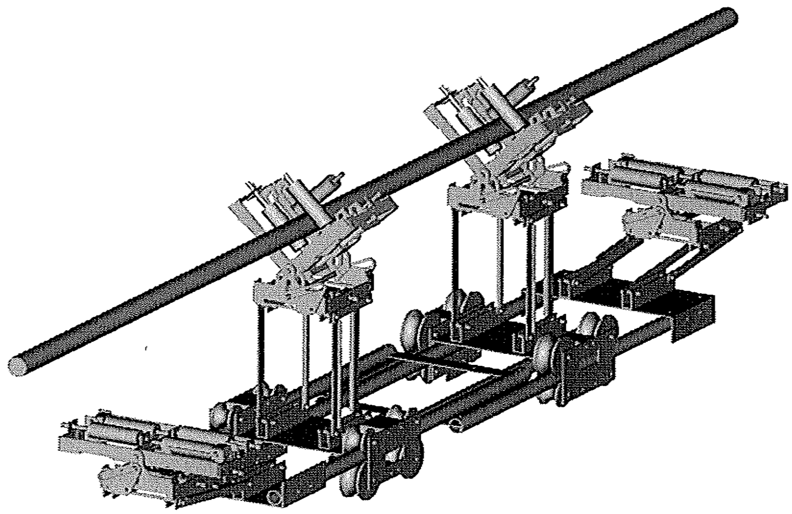


Figure 2.1 Robot on the line.

This robot has the following functional components (see Figure 2.2):

1) *Base.* A base is the robot's frame for supporting other components, electronic equipment, and a payload.

2) *Gripper.* A gripper provides two essential functions:

   a) *Holding an overhead line.* There are two possible states of the gripper: "Opened" and "Closed". In the state "Closed", the gripper holds the wire and in the state "Opened", the gripper stays free. During the transition from "Opened" to "Closed", the gripper grasps the line. Design of the gripper allows grasping lines and objects of varying diameters, functions that are very important in case of icy wires or sudden obstacles. The transition from "Closed" to "Opened" releases the line.

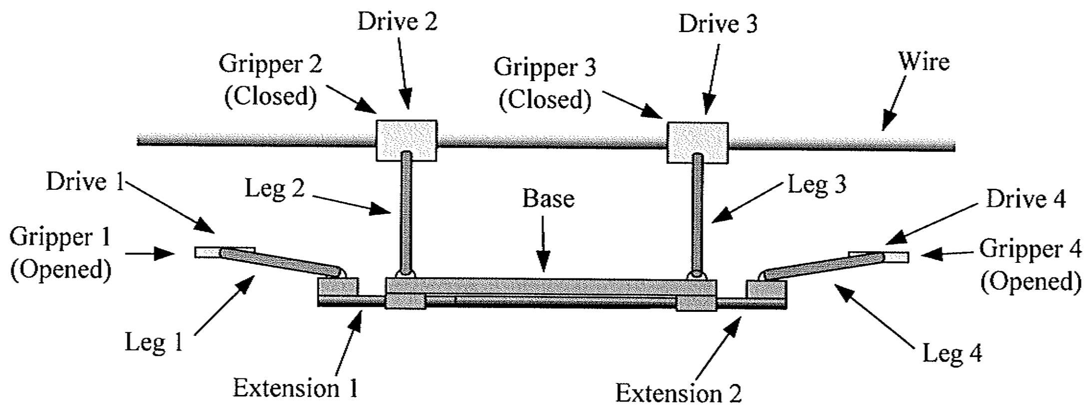


Figure 2.2 Main components of the robot

b) *Moving the robot along the overhead line.* Being equipped with wheels and driving servo systems, the gripper provides translational motion of the robot. This function is available when the gripper is in the state "Closed".

3) *Leg.* A leg can be represented by a lever connected to the base and to the gripper.

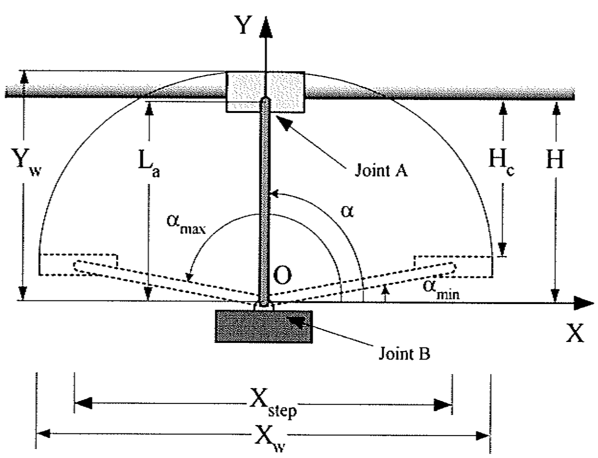


Figure 2.3 Working principle of Leg

Legs perform the following functions:

Delivering a gripper to the required location on the line. The gripper can be delivered within certain limits in both horizontal and vertical directions. The leg declines about the joint B on angle α, delivering the gripper to the line within the arc of radius L_a as shown in Figure 2.3.

Physical parameters of the leg determine its limitations, such as a length of a step X_{step}, distance from the gripper to the line (clearance) H_c, horizontal and vertical sizes of a "leg plus gripper" workspace X_w and Y_w, distance from the base of the robot to the line H.

Parameters of the leg:

L_a – length of the leg

α - angle of inclination

a) *Moving the base in horizontal and vertical directions.* Once the gripper grasps the overhead line, the leg can move the base in the vertical direction, reducing the clearance between the base and the line. In this case, the leg inclines about joint A on angle α, reduces the clearance H_c and advances the base in a horizontal direction.

4) *Base Extension.* The base extensions are the links connected to the foundations of the leg 1 and the leg 4, and slide along supports connected to the base. They serve for the following purposes:

a) *Translation of the leg 1 and the leg 4 in a horizontal direction.* This motion is restricted to the length of the base extensions X_{ext} (see Figure 2.4). The motion is possible when the gripper 1 and the gripper 4 are in the state "Opened", and the grippers 2 and 3 are in the state "Closed".

b) *Translation of the base in a horizontal direction.* This motion is performed when the gripper 1 and the gripper 4 are the state "Closed", and the grippers 2 and 3 are the state "Opened".

The following principles underlie the mechanical design:

1) Simplification of mechanical design by providing more sophisticated control algorithms, hardware, and software. These measures reduce the weight and the size of the robot and relax requirements for servos torques and the power supply of the robot. They also enhance the reliability of the mechanical design and the cost-to-production of the robot.

2) Provision of the robot with as much maneuverability as possible giving it the ability for different types of motion.

3) Equipment of the grippers of the robot with wheels and extension of the base of the robot in length. These features provide horizontal motion of the robot.

4) Equipment of the robot with legs. This feature will allow the robot to move in horizontal and vertical directions.

5) Combination of a gripper and a driving wheel into one unit.

6) Allowance of change of the robot's shape by increasing the linear size of the base from X_{base} to X_{linear}. This feature increases considerably the workspace of the robot and allows it to avoid long obstacles (see Figure 2.4).

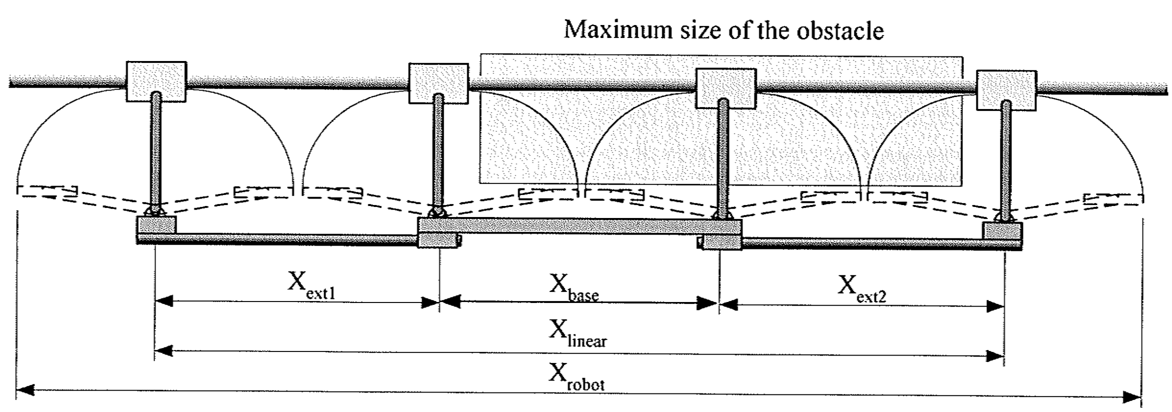


Figure 2.4 Correlation between size of robot and size of obstacle

1.1 Basic movements of the robot

The ability of the robot to move along the line is a crucial requirement of its capability to accomplish a mission. The robot should provide reliable means of motion, required quality of motion that may include different speeds and consumed energy profiles, motion on icy lines or lines with damaged strings.

There are three different types of motions that the robot can provide. They are used for specific purposes, differ in utilization of robot's components and subsystems, and have different power efficiency and speed. In case of failure of a component of the robot, the type of motion that excludes this component may be chosen, enhancing the whole reliability of the robot.

1.1.1 Wheeled motion (sliding along the line)

Integration of a driving unit into a gripper allows using the gripper for the horizontal motion. When the gripper grasps the line, the driving unit, using built-in wheels, moves the robot in a desired direction along the line. The robot can change its shape for adapting this motion for different tasks. There are many possible configurations the robot can take. Each of them can be effective in a particular situation and can mobilize all the capabilities of the robot for solving specific tasks.

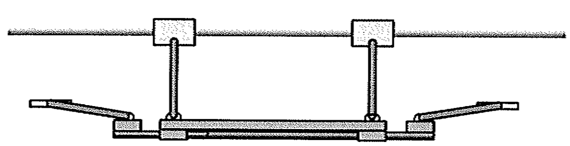


Figure 2.5 Wheeled motion: high-speed configuration

Figure **2.5** shows the robot with a shape that uses only two out of four driving units. This configuration provides the most economical longitudinal motion of the robot in both directions. The electrical power left from not working drives, may be used by the payload or by working drives for increasing the speed of the motion. The wheeled-motion configuration is the most effective when the robot approaches obstacles. Sensors, located in closed grippers detect the obstacle in horizontal (forward) direction and opened grippers detect the obstacle in vertical (bottom-up) direction, providing precise information about position of the robot relative to the obstacle.

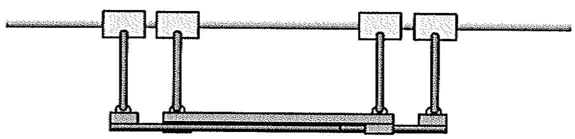


Figure 2.6 Wheeled motion: heavy-duty configuration

The Heavy-duty configuration is shown in Figure 2.6. It is a less economical type of motion, but the robot has an extra torque from driving units of the first and the forth legs. This allows the robot to move along areas where the line has big slopes.

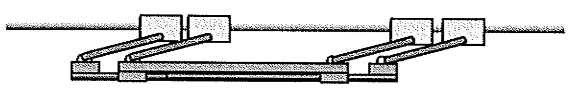


Figure 2.7 Wheeled motion: Reduced clearance configuration

The robot has an ability to reduce the distance (clearance) between its body and the overhead line (see Figure 2.7). In this way, the robot can approach the payload to the wire or anticipate a lateral wind. This motion can be used for monitoring lines or for the longitudinal motion in the presence of a strong wind.

Other configurations of the robot are possible and their usage depends on their advantages in particular situations.

1.1.2 Earthworm-like motion

The Earthworm-like motion utilizes the property of the base extensions to move in longitudinal directions. If grippers of the base are closed, and the grippers of the base extensions are open, then pushing off the base extension from the base causes the base extension to advance in a longitudinal direction. But when the grippers of the base extensions are closed and the grippers of the base are opened, then the attempt of the base to pull on the base extension causes the base to advance in the longitudinal direction. Repetitive push-offs and pull-ons of the extensions, opening and closing the grippers in predetermined sequence create the Earthworm-like motion of the robot.

Complex motion of the robot can be described by the State-Transition Diagram, which is similar to gaits [Todd85], and can be expressed as a function of time. The State-Transition Diagram describes a repetitive pattern of motions for the base extensions and states for the grippers. Only those components which participate in a motion appear in the diagram. It is assumed, that for the Earthworm-like motion, all legs of the robot are in vertical positions and all the driving units are stopped.

There are two possible types of the Earthworm-like motion.

Type 1

This type of the motion is described by the State-Transition Diagram shown in Figure 2.8. More detailed description is given in Figure 2.9 which shows the motion of the robot in the direction from right to left.

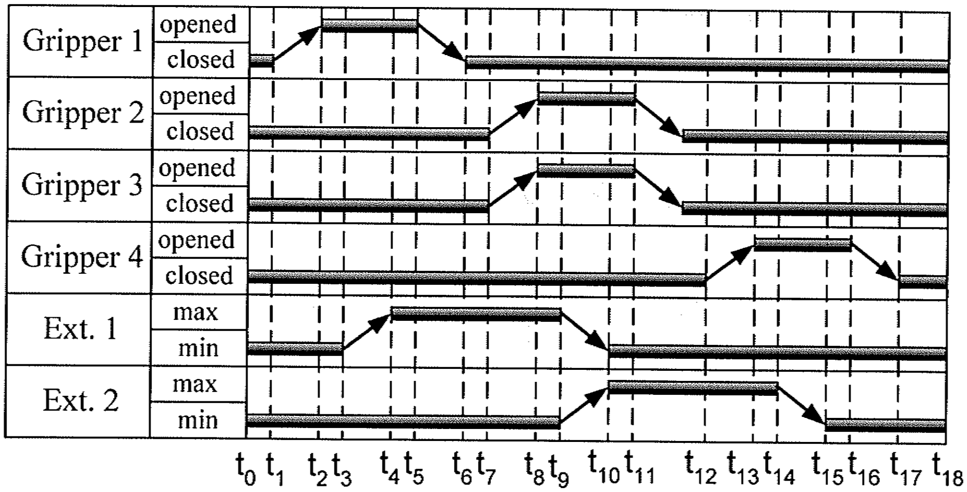
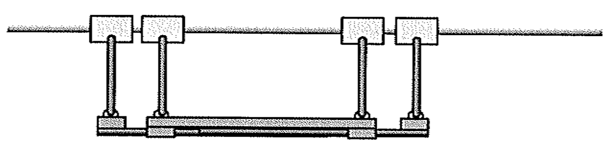


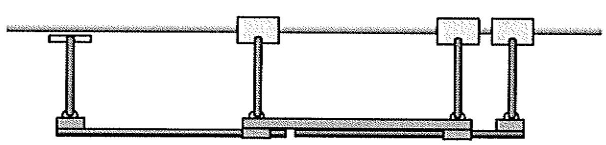
Figure 2.8 State-Transition Diagram for Earthworm-like motion, Type 1



a)

Time: t_0-t_1

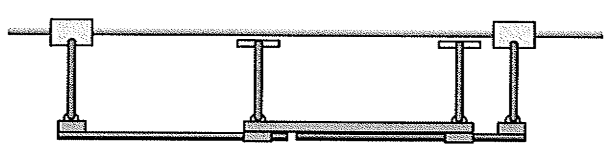
The robot is in the initial position.



b)

Time: t_1-t_5

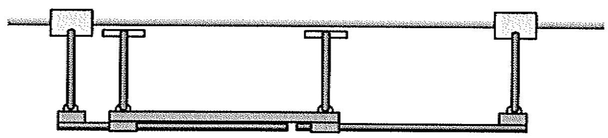
The first gripper opens and the first base extension moves forward at maximum distance.



c)

Time: t_5-t_9

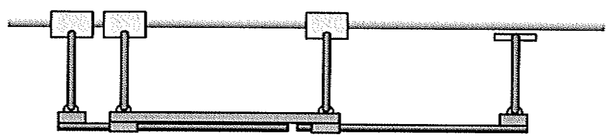
The first gripper grabs the line. The grippers of the base release the line.



d)

Time: t_9-t_{11}

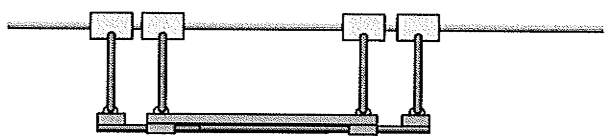
The base pulls-on the first extension and pushes-off the second extension. This action moves the base forward.



e)

Time: t_{11}-t_{14}

The grippers of the base grab the wire. The gripper of the second extension releases the line.



f)

Figure 2.9 a-f: Earthworm-like motion, Type 1.

Time: t_{14}-t_{18}

The base pulls-on the second extension. The gripper of the second base extension grabs the overhead line.

Thus, the robot advance in longitudinal direction at the distance equal to the length of a base extension.

Type 2

This type of Earthworm-like motion has similar transition and state patterns from t_0 to t_{11} and is shown in Figure 2.10. The differences between Type 1 and Type 2 motions begin from time t_{12}. The featured part of Type 2 motion is shown in Figure 2.11. The robot moves in the direction from right to left

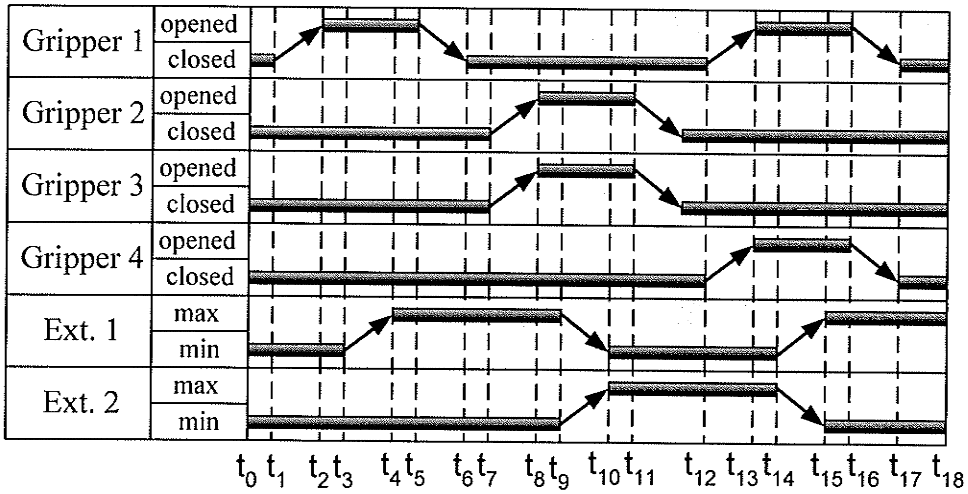
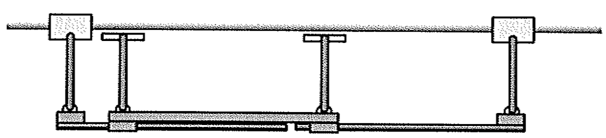
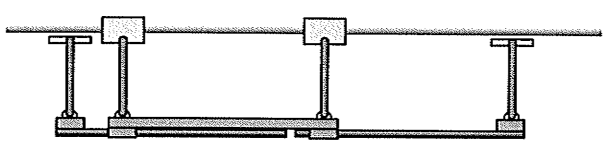


Figure 2.10 State-Transition Diagram for Earthworm-like motion, Type 2.



a)

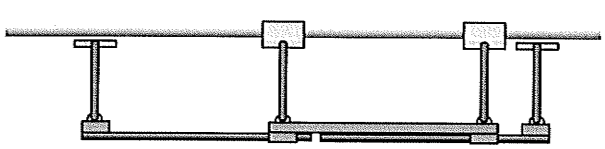
Time: t_{11}



b)

Time: t_{11}-t_{15}

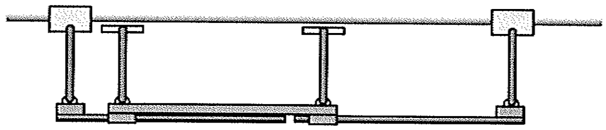
The grippers of the base grab the line. The grippers of the base extensions release the line.



c)

Time: t_{15}-t_{17}

The base pushes-off the first base extension and pulls-on the second base extension.



d)

Figure 2.11 a-d: Earthworm-like motion, Type 2.

Time: t_{17}-t_{19}

The grippers of the base extensions grab the line. The grippers of the base release the line. The robot is ready to repeat the next phases of patterns b-d (Figure 2.11), of t_{11}-t_{19} (Figure 2.10).

Type 2 of motion is effective when the robot moves on icy lines or when Wheeled motion is impossible for some reasons.

1.1.3 Legged Locomotion

Legged locomotion utilizes the property of a leg to move the robot's body in both vertical and horizontal directions (i.e. curvilinear translation). This happens when the grippers of acting legs hold the line and the legs simultaneously deflect on the same angle with the same angular speed. By applying different repetitive activation patterns for legs and grippers, the robot has the ability to stride along the wire. Driving units of the robot, at this motion, are in the stopped state and the base extensions are at maximum distance from the base, which allows the second and the third legs to deflect in a full range of angles.

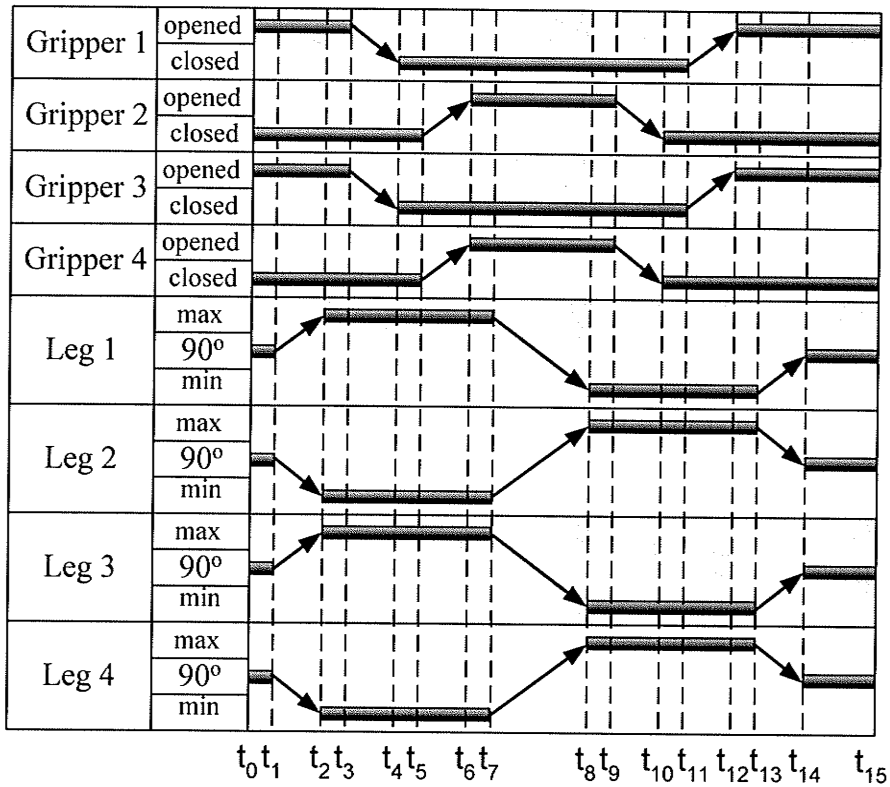
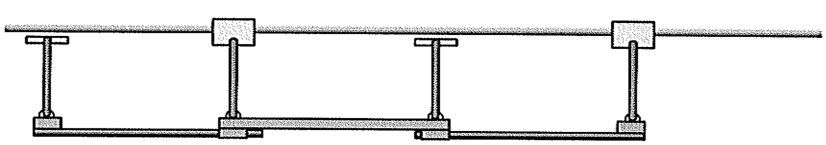


Figure 2.12 State-Transition Diagram for Legged locomotion

Legged locomotion is described by the State-Transition Diagram shown in Figure 2.12 and explained in detail in Figure 2.13. The robot moves in the direction from right to left.

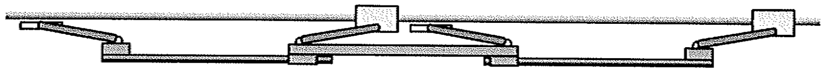


a)

Time: t_0-t_1

The robot is in the initial position. The base extensions at maximum distance, the first and the third grippers are opened.

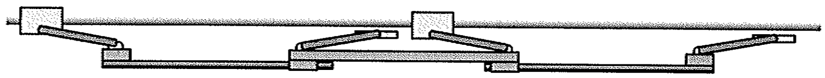
Time: t_1-t_3



b)

The first and the third legs deflect to a maximum angle. The second and the forth legs deflect to the minimum angle. The body of the robot moves forward and up.

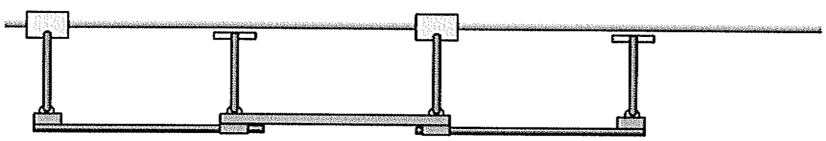
Time: t_3-t_7



c)

The first and the third grippers grab the line. The second and the forth gripper release the line. The first and the third legs start deflecting to minimum angle. The second and the forth legs deflect to the maximum angle.

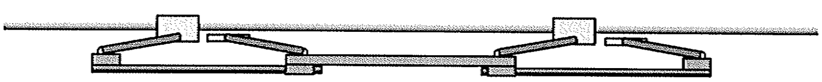
Time: t_7-t_8



d)

This is the intermediate state. All legs have reached the angle 90 degrees. They continue rotational motion.

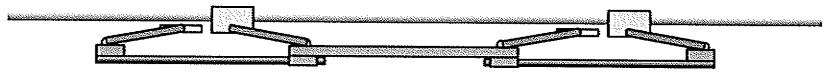
Time: t_9



e)

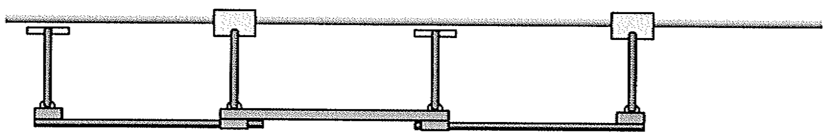
The robot has advanced in the horizontal direction.

f)



Time: t_9-t_{13}

The second and the forth grippers grab the line. The first and the third grippers release the line. The second and the forth legs start deflection to the minimum angle. The first and the third legs deflect to the maximum angle.



g)

Time: t_{14}

The robot has reached the initial position after having made 2 full steps.

Figure 2.13 a-g: Legged locomotion

1.2 Basic obstacle avoiding maneuvers

The combination of basic movements and the ability of the robot to change its shape, allow the robot to perform complex maneuvering on the line and avoid different types of obstacles. The robot uses the following criteria for selecting the proper sequence of movements:

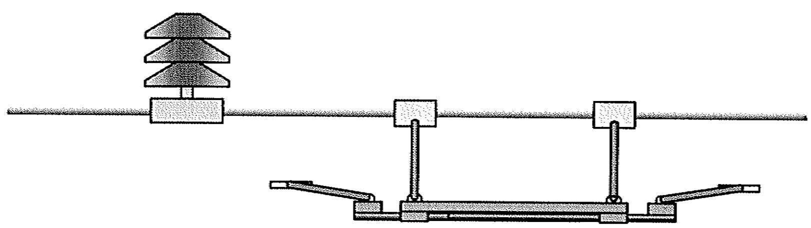
- obstacle avoiding should be done with minimal set of motions
- obstacle avoiding should be done with minimal power consumption
- obstacle avoiding should be done within restricted interval of time (i.e. the shorter the better).

This criterion requires the robot to be in close distance for a minimum time interval with the obstacle to prevent collision of the robot with the obstacle

The following obstacle avoiding algorithms are only two out of a numerous number possible variants for avoiding small and large obstacles on an overhead line.

1.2.1 Avoiding small obstacles

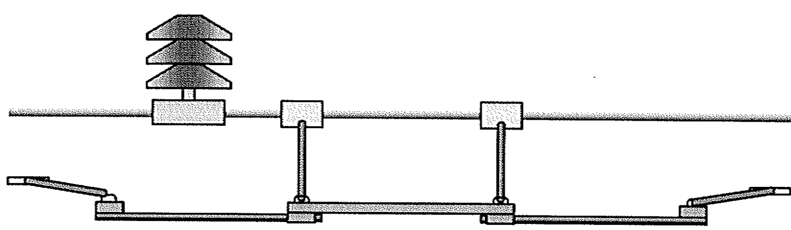
This type of maneuver is described by the State-Transition Diagram shown in Figure 2.15 and explained in detail in Figure 2.14.



Time: t_0-t_1

The robot is in the initial position.

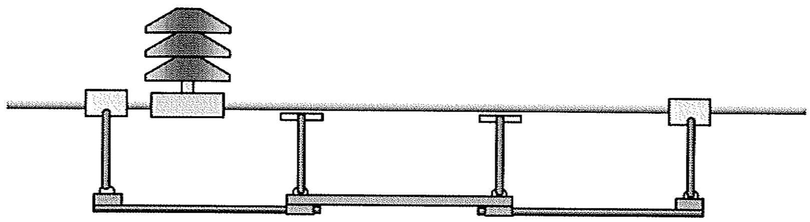
a)



Time: t_1-t_5

The robot approaches the obstacle using the third and the second driving units, pushes-off the base extensions at maximum distance

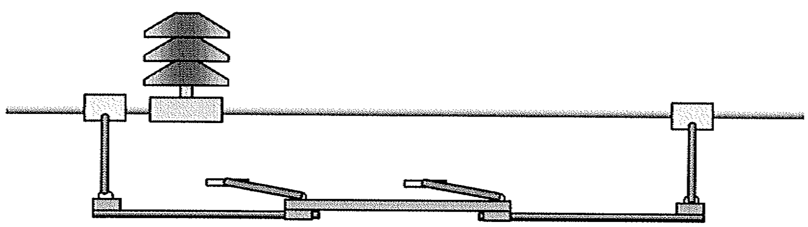
b)



c)

Time: t_5-t_{11}

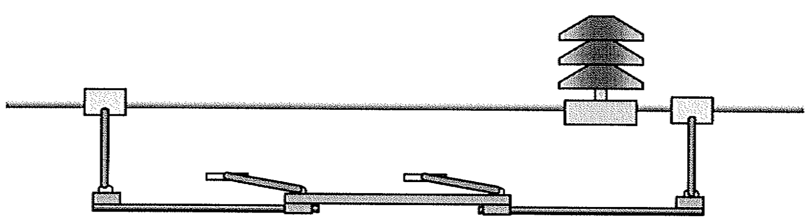
The first and the fourth legs deflect to the vertical position and their grippers grasp the line. Grippers of the base release the line.



d)

Time: t_{11}-t_{13}

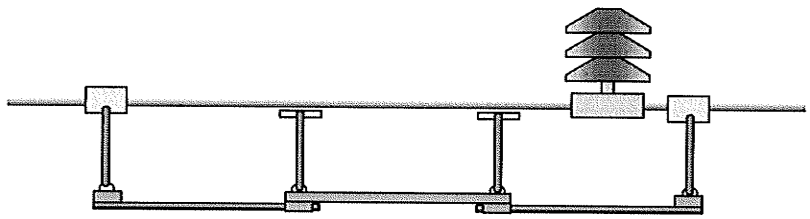
The base legs deflect to the maximum angle.



e)

Time: t_{13}-t_{17}

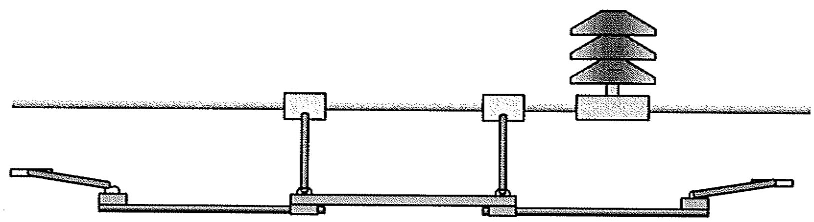
The robot advances forward using the driving units of the base extensions.



f)

Time: t_{17}-t_{19}

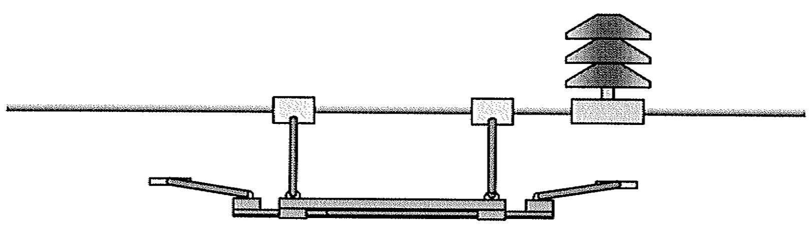
The legs of the base deflect to the vertical position.



g)

Time: t_{19}-t_{25}

The base grippers grasp the line. The grippers of the base extensions release the line. The first leg deflects to the maximum angle and the fourth leg deflects to the minimum angle.



h)

Time: t_{25}-t_{27}

The robot pulls-on base extensions and prepares for a next motion.

Figure 2.14 a-h: Avoiding small obstacles

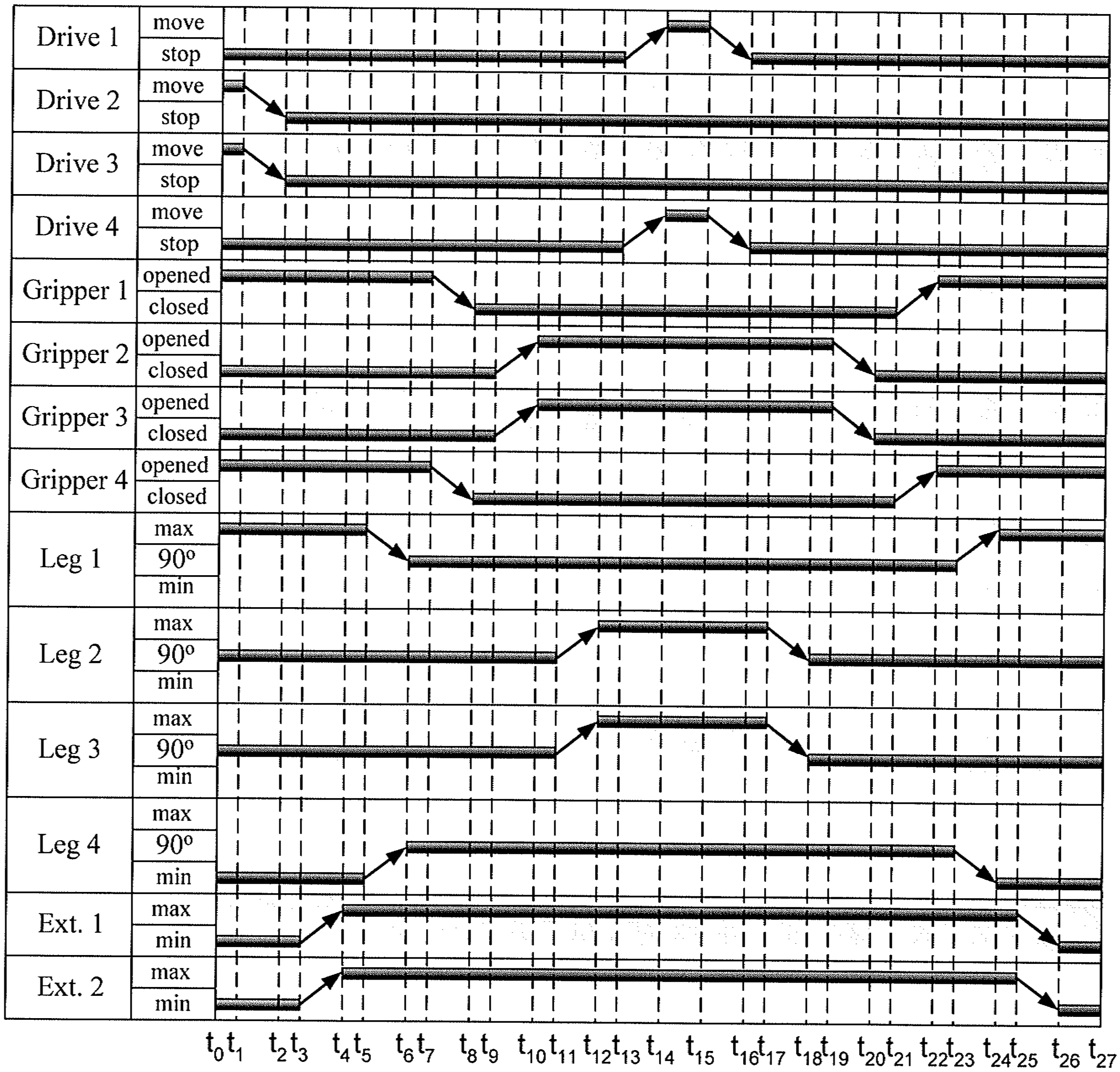
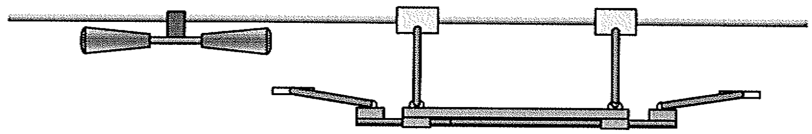


Figure 2.15 State-Transition Diagram of avoiding small obstacles

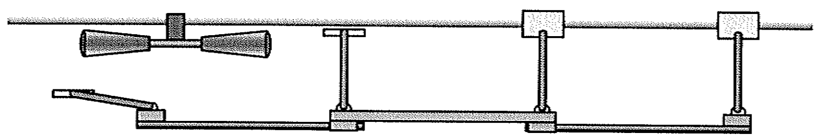
1.2.2 Avoiding large obstacles



a)

Time: t_0-t_1

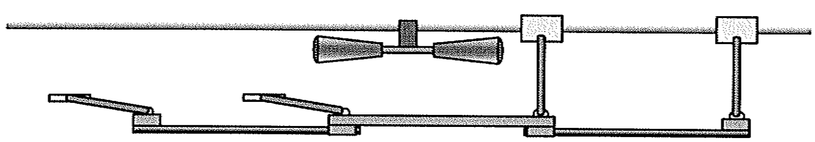
The robot is in the initial position.



b)

Time: t_1-t_5

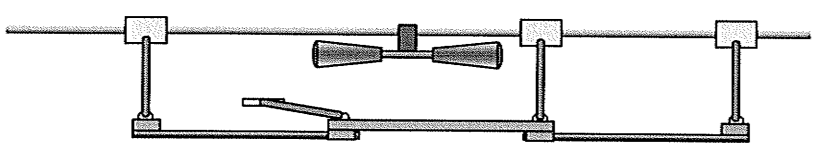
The robot pushes-off the second base extension, deflects its leg to the vertical position and grasps the line. Then, the robot pushes-off the first base extension and the second gripper releases the line.



c)

Time: t_5-t_{10}

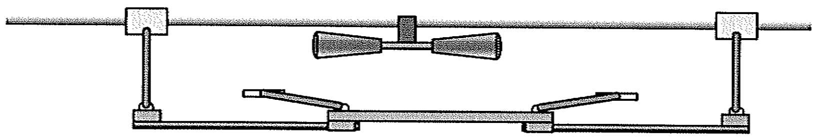
The second leg deflects to the maximum angle using the driving units of the third and the forth leg. The robot advances forward.



d)

Time: t_{10}-t_{14}

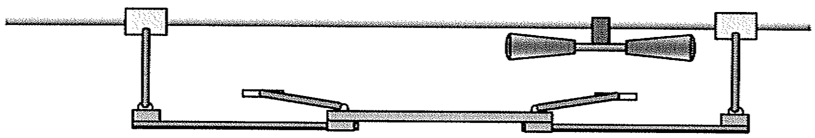
The first leg deflects to the vertical position and its gripper grabs the line.



e)

Time: t_{14}-t_{18}

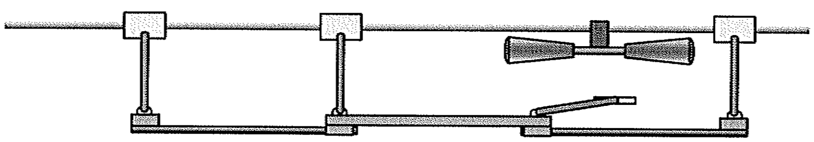
The third gripper releases the line and its leg deflects to the minimum angle.



f)

Time: t_{18}-t_{22}

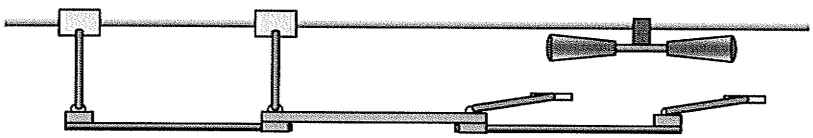
The robot advances forward using the first and the second drivers.



g)

Time: t_{22}-t_{26}

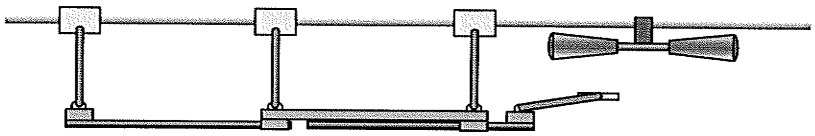
The second leg deflects to the vertical position and its gripper grabs the line.



h)

Time: t_{26}-t_{32}

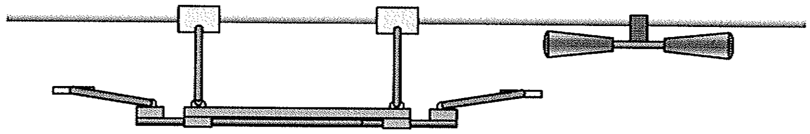
The forth gripper releases the line and its leg deflects to the minimum angle. The robot starts to move forward.



i)

Time: t_{32}-t_{38}

The robot moves forward until the third leg has enough room to take the vertical position and grasp the line.



j) **Figure 2.16 a-j: Avoiding large obstacles**

Time: t_{38}-t_{46}

The first gripper releases the wire and its leg deflects to the minimum angle. The robot pulls-on the base extension and takes the position for a next motion.

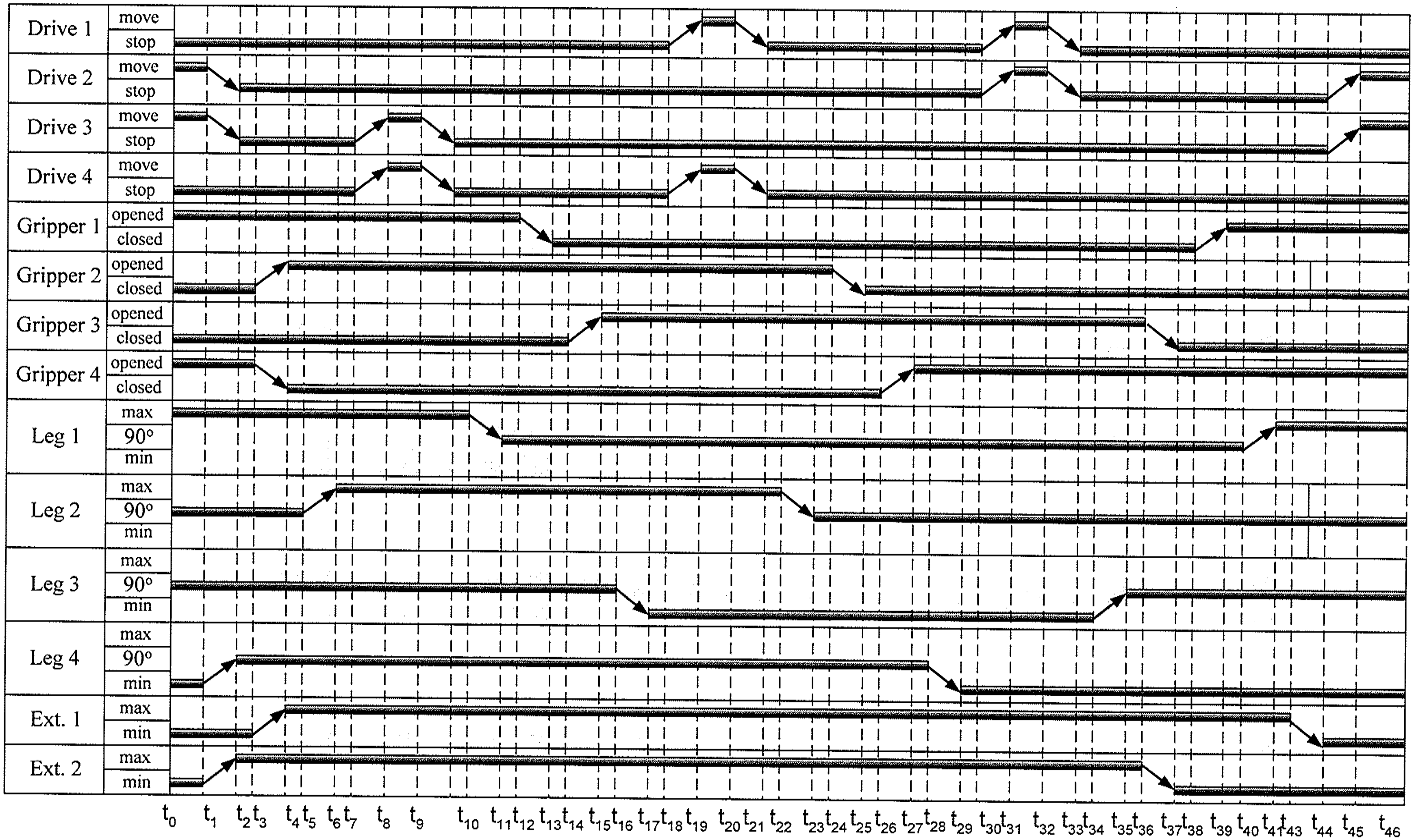


Figure 2.17 Avoiding large obstacles

3 The architecture of the control system of the robot

An architecture of a control system is a well-ordered set of approaches and principles which underlie the design of the control system to provide the required functionality of the robot. Environmental conditions and technical requirements for the robot play a crucial role in the selection of the structure of the control system.

In order to explore all capabilities of the robot, the conditions of operation of the robot and some principles of the control system should be considered in detail.

The robot should be resistant to all kinds of environment. The robot is a mobile autonomous system which is designed to work in distant areas for long periods of time. During the mission, the robot is influenced by the natural factors such as rain, strong wind, frost, heat, and icing. The ability to anticipate those factors determines the functionality and the flexibility of the robot. In order to be resistant to all kinds of weather conditions, the robot is equipped with different types of environmental sensors. The wind can cause serious problems for the root or its payload, especially, when the robot is in its obstacle-avoiding manoeuvre. The robot operates on high voltage transmission lines and it should also pay attention and, if necessary, take appropriate steps, if there is a partially damaged line or other unexpected obstacle is on the robot's way.

The robot should be reconfigurable. The mission of the robot is to provide a mobile service to different types of a payload. This requires the robot to be easily reconfigured for a particular type of the payload equipment which is determined by the mission of the robot. For this, the algorithms of the control system should be flexible, adoptable, expandable, simple, and keep at the same time the required functionality. The control system should provide the optimal motion and manoeuvres which are specific to a particular set of payload equipment.

The robot should be reliable. During the work on the line, some subsystems of the robot may fail. The redundancy of the control system becomes essential. The system should compensate, to some degree, failed subsystems by reconfiguration and redistribution of resources of the robot.

The robot should have a friendly interface. The interface of the control system should provide an easy human-robot interaction by making the system easy for manual operation, clear and simple for modifications and cooperation in a mission. The operator should easily control all recourses of the robot. In addition, the control system should be simple and, that is very important, predictable at any time of operation of the robot.

The block-diagram of the control system of the robot is shown in Figure 3.1. The control system of the robot is a hybrid system which combines deliberative planning, behavioral, and feedback control.

The main idea behind the introduction of behaviors is to avoid the uncertainty of the surrounding environment which directly or indirectly influences the controlled object. It is impossible to predict every situation which the robot might encounter. But, it may be possible to anticipate the situations and, by applying the reconfigurable mechanism of selection behavior, adjust the robot to current environment and conditions.

Figure 3.1 shows four different levels of control. They are a level of deliberative planning, a level of high-level behaviors, a level of low-level behaviors and a level of feedback controls.

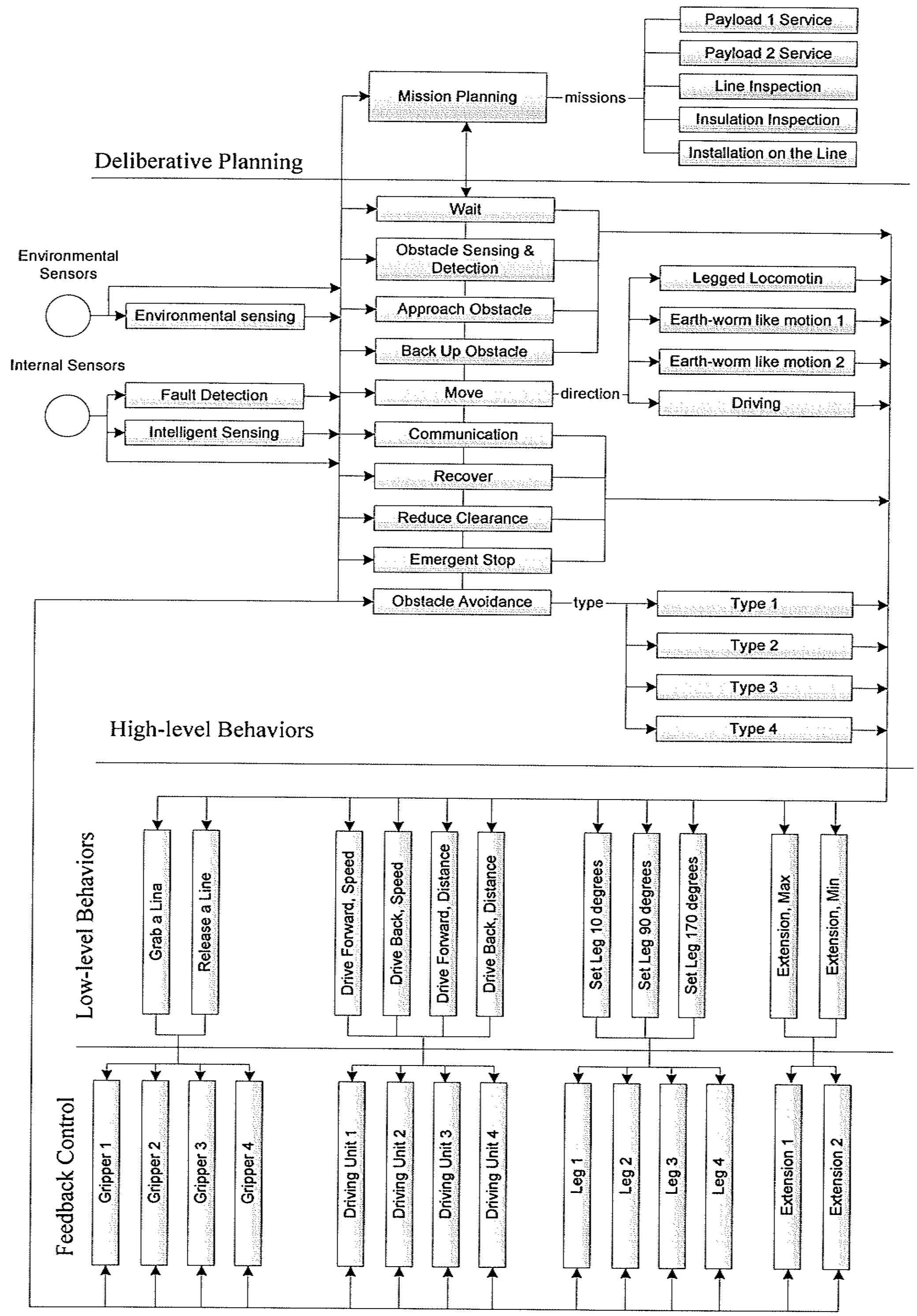


Figure 3.1 Structure of control system of robot

The level of deliberative planning is responsible for coordination of behaviors according to the mission of the robot. It analyses the sensor information about the internal states of the robot and the undertaken actions. The final word in selecting behaviors belongs to this layer. This layer also performs mission rescheduling and reconfiguration of the robot.

The level of high-level behaviors contains a set of behaviors or actions which the robot can choose for its operation. All behaviors gather sensor information and prepare appropriate actions. But the action of the robot can be activated under the specific conditions only. These conditions are determined by the level of deliberative control and the priority of the behavior. The high-level behaviors may consist of other high-level behaviors or low-level behaviors.

The level of low-level behaviors contains a simple set of actions directing the servo systems of the robot. These behaviors are called by high-level behaviors after their decomposition. The low-level behaviors can also be called by the Deliberating level, when the system goes under the supervising control of the human-operator or if the deliberating level reconfigures the system and the direct actions of servos are required.

The level of feedback control implements a traditional proportional-integral-derivative (PID) control algorithm for controlling the servo system. The input for a feedback controller is supplied by low-level behaviors upon the command from the level of high-level behaviors with the authorization of the deliberative planner.

The control system of the robot comprises all elements required for gathering information about the state of the robot and the surrounding environment, selecting the appropriate action and its execution.

4 Low level control

4.1 Control system of legs

The ability of the robot to keep a sustained stable motion in a specified direction and avoid obstacles to a great degree depends on the robot's ability to control its legs. By changing angles of inclination and working synchronously or independently, legs allow the robot to take numerous configurations and generate many different motions.

There are two modes in which the legs operate: a *single leg* mode and a *cooperative* mode. In the single leg mode, each leg is controlled individually. This mode is used for deflecting a leg regardless of the current positions or motions of other legs. Each leg has its own digital controller that provides a unique control input for the leg's actuator. In the cooperative mode, a digital controller is dedicated to a number of legs and generates control signals that move legs synchronously.

4.1.1 Single leg mode

The single leg mode is the most frequently used mode in which the robot operates. This mode is in use when the robot places a leg into a particular position of a workspace, inserts a leg behind an obstacle, grasps the line or releases the line. In all these situations, a leg is used as a carrier of a gripper and action of the robot is directed towards the positioning of a gripper in a required workspace location.

4.1.1.1 Mathematical model

A basic action of the robot, grasping the line, begins from rotation of a leg from its initial angle position α_{min} (or α_{max}) about the joint O to the angle α (see Figure 4.2).

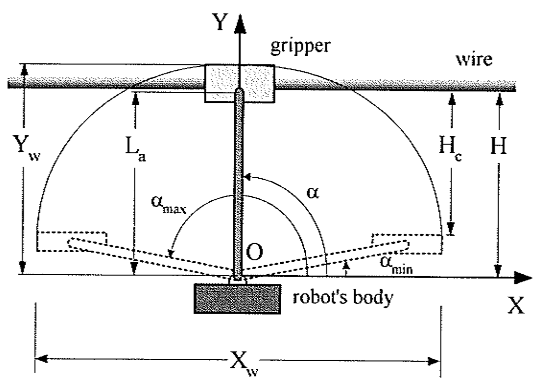


Figure 4.2 Single leg mode

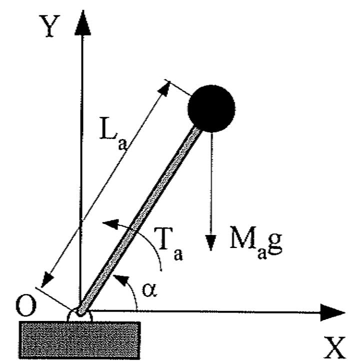


Figure 4.1 Model of a leg

At this angle, the gripper is close enough to the line to grasp and hold it. In order to rotate the leg, the actuator of the leg, directly coupled to the joint O, should provide the torque T_a which overcomes the moment of weight of the leg's gripper, the moment of inertia of the leg and the Coulomb friction in the joints of the leg. For calculation of the actuator torque T_a, the leg can be represented by a model of an inverted pendulum with the mass M_a, and the weightless link of length L_a. (Figure 4.1) The leg rotates about the joint O at angle α within the range $\alpha_{min} < \alpha < \alpha_{max}$.

The required actuator torque T_a can be found as:

$$T_a = J_a \cdot \frac{d^2\alpha}{dt^2} + M_a \cdot L_a \cdot g \cdot \cos\alpha(t) + M_a \cdot g \cdot R_a \cdot \sin(\tan^{-1}(\mu_a)) \cdot sign(\dot{\alpha})$$ **Eqn. 4-1**

where:

M_a - mass of the gripper, [kg]

L_a - length of the leg, [m]

$J_a = M_a \cdot L^2{}_a$ - moment of inertia of leg [$kg{\cdot}m^2$]

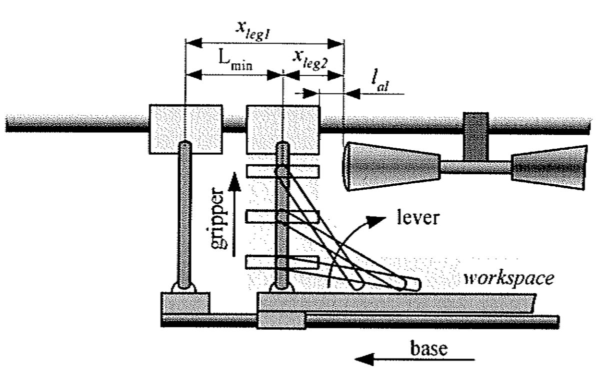
g - acceleration of gravity, [m/sec^2]

R_a - radius of the support axle of the leg's joint, [m]

μ_a - coefficient of kinetic friction, [-]

α - angle of deflection of leg, [rad]

Applying the torque T_a, the leg can be turned to the desired angle. Thus, the gripper, located at the end of the leg, performing a curvilinear translation, can be moved to the specified location for a maneuver or to grasp the line. The ability of the robot to control X and Y coordinates of the gripper adds flexibility in designing different types of



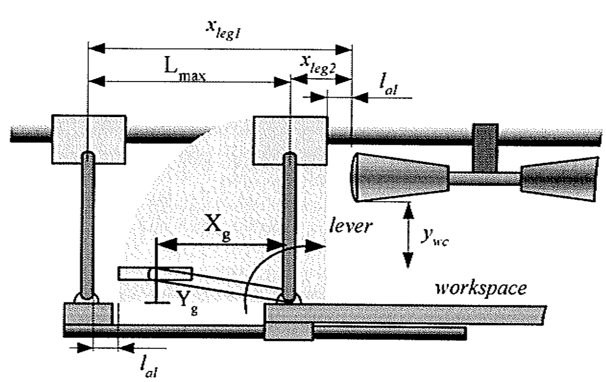


Figure 4.4 Placing leg behind obstacle, Type 2. Figure 4.3 Placing leg behind obstacle, Type 1.

motions.

One of the most critical maneuvers of the robot is an obstacle avoidance. To accomplish this maneuver, the robot must be able to place at least two legs behind the obstacle. This procedure is associated with the risks of collisions - the second leg into the first one, which is already placed behind the obstacle, or colliding the second leg into the obstacle.

A possible way of insertion of the second leg behind the obstacle is shown in Figure 4.3. Obstacle avoidance maneuver begins with positioning the first leg behind the obstacle at a distance not less then x_{leg1} from the edge of the obstacle. This will provide enough space for a workspace of the second leg and a safety allowance l_{al}. Next, the base of the robot moves forward until it reaches x_{leg2}. Rotational motion of the second leg to the angle $\alpha=90^{\circ}$ ends the procedure. This method is simple but it has disadvantages – the workspace for performing this procedure is considerably large and requires relatively longer linear sizes of the robot, both for the base and base extensions, increasing the total weight of the robot (and consequently requiring greater powers for servos and amplifiers).

The alternative way of placing the second leg is to combine a rotational motion of the leg and a linear motion of the base simultaneously (see Figure 4.4). In this case, the first leg is placed at a distance x_{leg1}, which is equal to two safety allowances l_{al} and a minimal distance between the base and the first leg L_{min}. When the first leg grasps the line, the base of the robot moves forward. As soon as the gripper of the second leg is at distance x_{leg2} from the edge of the obstacle, it begins rotational motion. A control system stabilizes the second gripper at the distance x_{leg2}, providing necessary angular speed for rotation of the leg and linear speed of the base. When the base of the robot reaches x_{leg2}, the leg stops. At the same time, the second leg completes the rotational motion, placing the gripper between the obstacle and the first leg. Advantage of this method is a significant decreasing the size of the workspace and reduction of the requirements to the linear sizes of the robot. However, a special care should be given to the coordination of these two motions.

Position of the gripper can be found from Eqn. 4-2:

$$\begin{bmatrix} X_g \\ Y_g \end{bmatrix} = L_a \cdot \begin{bmatrix} \cos\alpha & 0 \\ 0 & \sin\alpha \end{bmatrix} \quad \textbf{Eqn. 4-2}$$

Coordinated motion of the second leg and the base of the robot, for implementation of Type 2 obstacle avoidance maneuver, is possible under the condition that the horizontal speed of the gripper V_{gx} is equal to the horizontal speed of the base V_{bx}:

$$Vbx = Vgx \quad \textbf{Eqn. 4-3}$$

To satisfy this condition, the base adjusts its linear speed through the angular speed of the base servo drive. The tracking controller of the base follows the angular speed of the second leg according to Eqn. 4-4:

$$\omega_b = \omega_L \cdot \frac{L_a}{R_{wb}} \cdot \cos\alpha \quad \textbf{Eqn. 4-4}$$

where:

ω_b – angular speed of base's actuator, [rad/sec]

ω_L – angular speed of second leg, [rad/sec]

$R_{\omega b}$ – radius of base's drive wheel, [m]

4.1.1.2 Design of controller

A digital control system for a leg is shown in Figure 4.5. The supervising control system of the robot sets the required angle of deflection of the leg α_{req}. This value is a reference parameter for the digital controller of the leg. The digital controller produces a discrete time control signal $\overline{m}(kT)$ with a specified sampling time *T*, which is then converted to a continuous time signal $\overline{m}(t)$ by an amplifier. The output signal of the amplifier $u(t)$ feeds a DC motor that provides a required torque for rotation of the leg to an angle $\Theta(t)$. The digital controller monitors position of the leg by reading sensor data $\overline{\alpha}(t)$, converting it to the digital form $\overline{\alpha}(kT)$ and scaling to the appropriate for computing range $\alpha(kT)$. The output signal $\alpha(kT)$ is compared with the reference signal $\alpha_{req}(kT)$ and the error signal $\Delta\alpha(kT) = \alpha_{req}(kT) - \alpha(kT)$ is fed to the control algorithm. It produces a new control signal $\overline{m}((k+1)T)$ in order to compensate the error $\Delta\alpha(kT) = 0$. When the error signal equals to zero, the angle of deflection of the leg is equal to the reference angle $\alpha_{req} = \Theta$.

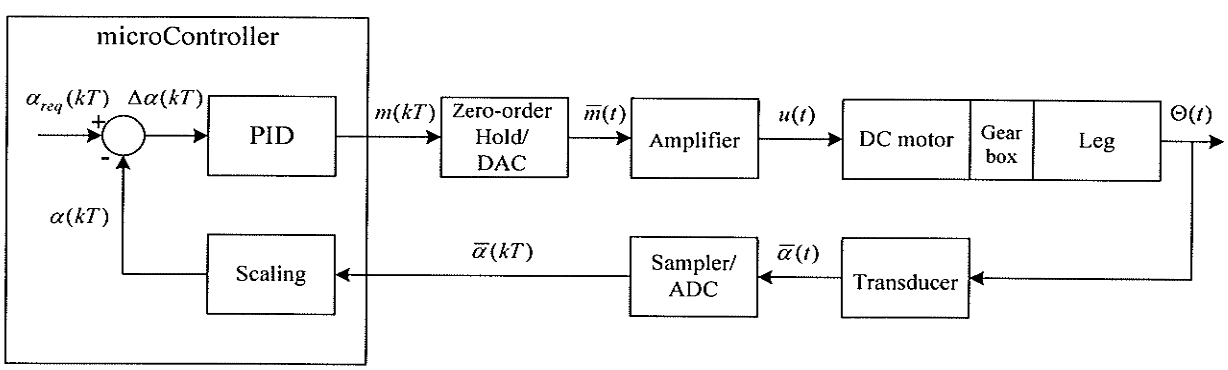


Figure 4.5 Block diagram of a digital control system

The value of the signal $\bar{m}(kT)$ equals to the voltage fed to the DC motor *u(t)*, and it is expressed in terms of volts but physically is represented by a data code. There is a chain of signal transformations between the output of the micro-controller and the input of the DC motor for converting the value of $\bar{m}(kT)$ to a voltage, see Figure 4.6.

Most of Digital-to-Analog Converters (DAC) used in control systems are unipolar devices, which means that they can provide only a voltage in the range from 0V to $U_{\max}^{DAC}$ volts with a resolution n bit. On the other hand, computed control signal $m(kT)$ can take positive or negative values and its magnitude can exceed the output magnitude of the DAC. In order to represent the whole range of values of the control signal $m(kT)$ within a limited unipolar range of the DAC, the control algorithm pre-scales the control signal $m(kT)$ to $\bar{m}(kT)$ using the following equation:

$$\bar{m}(kT) = m(kT) \cdot \frac{2^n - 1}{2 \cdot m_{\max}} + \frac{2^n - 1}{2} \qquad \textbf{Eqn. 4-5}$$

where:

$m(kT)$ - control signal, [V]

$\bar{m}(kT)$ - normalized control signal, [-]

$m_{\max}$ - maximum value of $m(kT)$, [V]

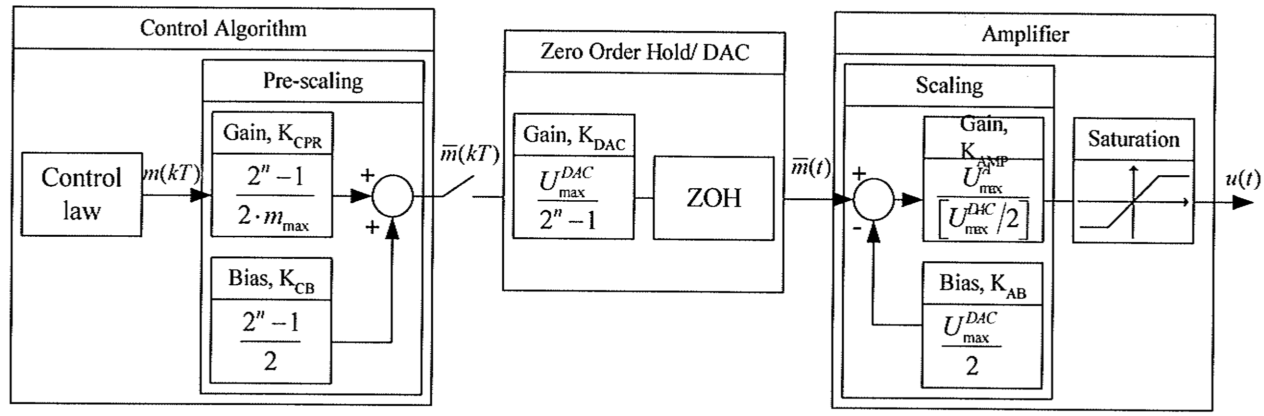


Figure 4.6 Path of a control signal

DACs are low current devices, so the output signal from the DAC should be amplified to provide the required current to the DC motor. Another reason for amplifying of $\overline{m}(t)$ is the necessity to scale the signal $\overline{m}(t)$ back to the original value of $m(kT)$:

$$u(t) = \overline{m}(t) \cdot \frac{U_{\max}^{A}}{\left[U_{\max}^{DAC}/2\right]} - \frac{U_{\max}^{DAC}}{2} \qquad \textbf{Eqn. 4-6}$$

where:

$u(t)$ - output signal from amplifier, [V]

$\overline{m}(t)$ - output signal from DAC, [V]

$U_{\max}^{A}$ - maximum output voltage of amplifier, [V]

$U_{\max}^{DAC}$ - maximum output voltage of DAC. [V]

The designed control system works at low frequencies and, it is assumed, that the amplifier has a constant gain for all working frequencies and operates in a linear region. Eqn. 4-7 gives the final expression for the output signal $u(t)$:

$$u(t)=\left[\sum_{k=0}^{\infty} m(kT)\cdot\frac{2^n-1}{2\cdot m_{\max}}\left[1(t-kT)-1(t-(k+1)\cdot T)\right]+\frac{2^n-1}{2}\right]\cdot\frac{U_{\max}^{DAC}}{2^n-1}\cdot\frac{U_{\max}^{A}}{\left[\frac{U_{\max}^{DAC}}{2}\right]}-\frac{U_{\max}^{DAC}}{2} \quad \textbf{Eqn. 4-7}$$

Reduction of Eqn. 4-7 yields to Eqn. 4-8:

$$u(t)=\frac{U_{\max}^{A}}{m_{\max}}\sum_{k=0}^{\infty} m(kT)\cdot\frac{2^n-1}{2\cdot m_{\max}}\left[1(t-kT)-1(t-(k+1)\cdot T)\right] \quad \textbf{Eqn. 4-8}$$

The similar idea underlies the reduction of measuring path $\Theta(t)\rightarrow\alpha(kT)$, which supplies the control algorithm with the true value of the leg's angular position. The simplified block diagram of the control system is shown in Figure 4.7:

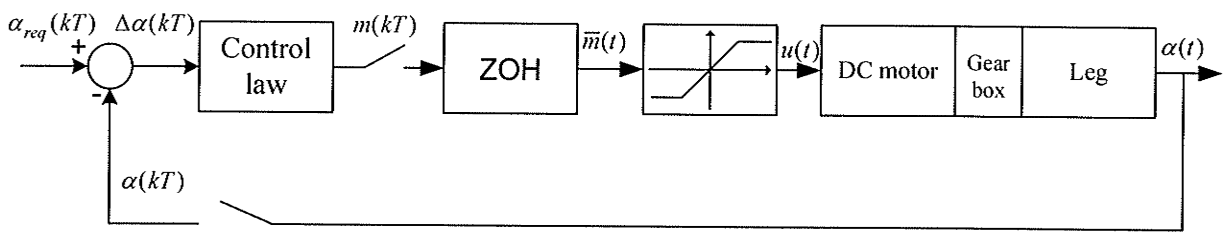


Figure 4.7 Simplified block diagram of a control system

In order to reproduce the output voltage $u(t)$ equal to the value $m(kT)$, the ratio $\frac{U_{\max}^{A}}{m_{\max}}$ should be equal to one. Additionally, the amplifier is subject to saturation and the DC motor to the restrictions on the maximum input voltage. Thus, the amplifier can be described by a saturation nonlinearity with a slope equal to one and with the saturation level U_{SAT}^{AMP}, which is less than the maximum input voltage of the DC motor. Figure 4.8 shows the equivalent block diagram of a digital control system of the leg.

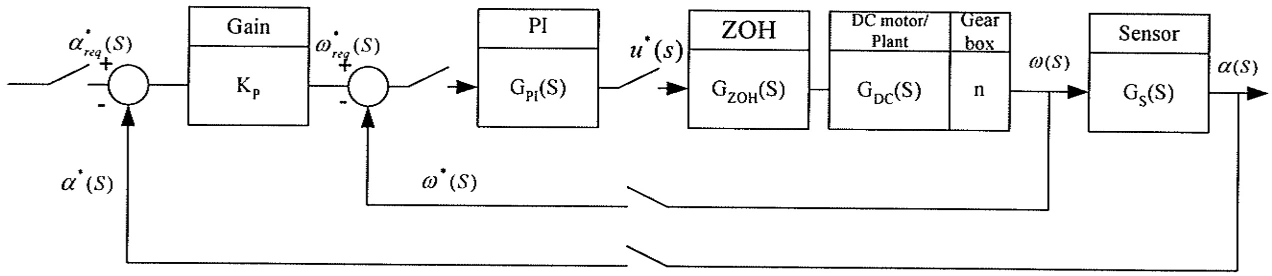


Figure 4.8 Digital control system of a leg

The transfer function $G_{ZOH}(s)$ of the zero-order hold (ZOH) is given by Eqn. 4-9:

$$G_{ZOH}(s) = \frac{1-e^{-Ts}}{s} \qquad \textbf{Eqn. 4-9}$$

Since the shaft position of the DC motor is an integral of the shaft angular speed, the transfer function of the ideal angular position sensor $G_S(s)$ can be represented by Eqn. 4-10:

$$G_S(s) = \frac{1}{s} \qquad \textbf{Eqn. 4-10}$$

The transfer function of the DC motor and the leg $G_{DC}(s)$ is expressed by Eqn. 4-11 and the block-diagram of the DC motor is shown in Figure 4.9.

$$\frac{\omega(s)}{u(s)} = \frac{n \cdot K_i}{L_a \cdot J \cdot s^2 + (R_a \cdot J + B_m \cdot L_a) \cdot s + (K_b \cdot K_i + R_a \cdot B_m)} \qquad \textbf{Eqn. 4-11}$$

where parameters of Eqn. 4-11 are given in Appendix A.1

The equivalent moment of inertia J from Eqn. 4-11 comprises the rotor inertia of the motor J_m and the inertia of the leg referred to the motor shaft J_a

$$J = J_m + J_a \cdot n^2 \qquad \textbf{Eqn. 4-12}$$

The output torque of the DC motor, which is applied to the leg, is the difference between the torque T to be generated by the motor and the external load disturbance torque T_L, see Figure 4.9.

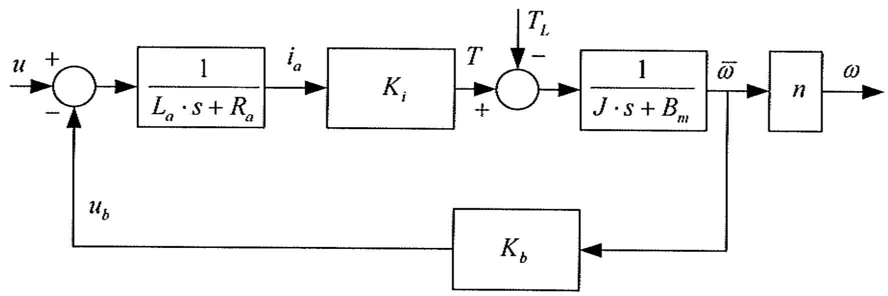


Figure 4.9 Block diagram of a DC motor/plant system

The load disturbance torque, generally, has a non-linear nature and is caused by the following factors:

- friction in joints of the leg, such as Coulomb friction
- the moment of weight of the gripper attached to the end of the leg
- other external factors such as a moment caused by wind or by an extra weight from icing leg

The major contributor to the disturbance torque is the moment of weight of the gripper. Changes to the dynamics of the system caused by load disturbances worsen the system performance, may lead to oscillations or to instability of the system, and therefore, they are unwanted factors that should be filtered or compensated.

It is assumed that the control system operates in a linear region.

Design of the PI controller

The transfer function of the open-loop DC motor/leg system is

$$G_{DC}(s) = \frac{20293.2637}{(s+1344)\cdot(s+65.58)} \qquad \textbf{Eqn. 4-13}$$

The type of the closed-loop system is zero. It means, that the system will always have the steady-state error between the reference signal ω_{req}, represented by a step function, and the regulated parameter ω. By introduction of the PI controller to the open-loop transfer function of the system, the type of the system can be increased by one and the steady-state error will become zero.

The starred Laplace transform of the DC motor and the zero-order hold, shown in Figure 4.8, is given by

$$\frac{\omega^*(s)}{u^*(s)} = G_{ZOH}G^*_{DC}(s) \qquad \textbf{Eqn. 4-14}$$

In terms of the z transform notation,

$$G_{ZD}(z) = Z\left[G_{ZOH}G_{DC}(s)\right] \qquad \textbf{Eqn. 4-15}$$

or

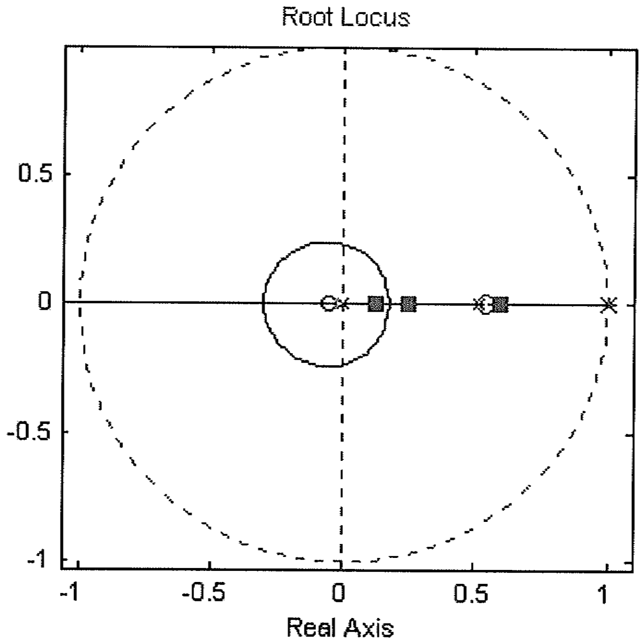
$$G_{ZD}(z) = \frac{0.1046\cdot(z+0.05861)}{(z-1)\cdot(z-1.459\cdot10^{-6})}, \quad \text{for T=0.01 sec} \qquad \textbf{Eqn. 4-16}$$

The root locus method is used for obtaining the PI controller coefficients. This method allows to evaluate the transient response and the stability of the system by location of the closed loop poles in the z plane.

The transfer function of the PI controller is obtained by moving the poles of the controller in the z–plane of the root locus shown in

Figure 4.10. The criteria for selection of the controller's poles is the stability of the closed loop system and the speed of the response of the system which should be without oscillations. The transfer function of the PI controller is expressed by Eqn. 4-17.

$$C_{PI}(z) = \frac{5.3002 \cdot (z - 0.546)}{(z-1)} = 2.8938 + \frac{2.4063}{1 - z^{-1}} \quad \textbf{Eqn. 4-17}$$



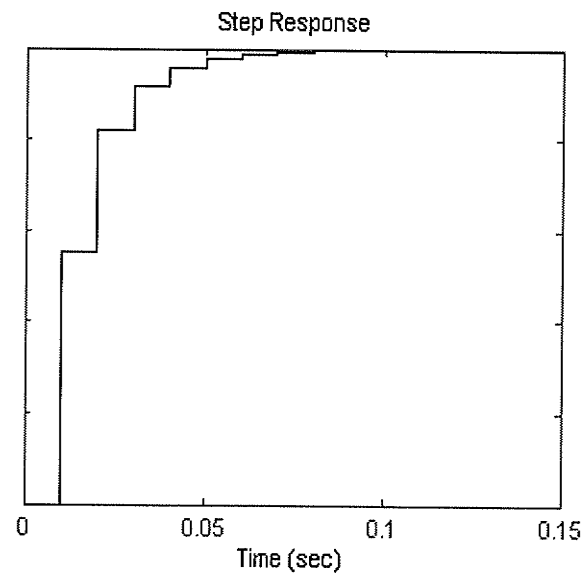


Figure 4.10 Root locus of inner loop **Figure 4.11 Response of inner loop**

Stability of the system can be evaluated from the location of the closed loop poles of the system on the root locus shown in

Figure 4.10. The closed loop poles lie within the unit circle in the z plane that makes the system stable. At the same time, the poles lie on the real axe close to the breakaway point providing the fast response, shown in Figure 4.11, with dumping ratio 0.93.

Choosing gain K_P

The regulated parameter of the DC motor/leg system is the angular speed of the leg ω, but the regulated parameter of the servo system of the leg is the angular position of the leg α. Thus, incorporation of the gain K_P in the forward path of DC motor/leg system provides the reference signal for the inner loop ω^*_{req} from the error signal between the actual angle and the required angles of the leg $\dot{\alpha}_{req} - \dot{\alpha}$.

The transfer function of the inner loop and the sensor for measurement of the angular position of the leg, shown in Figure 4.8, is expressed as

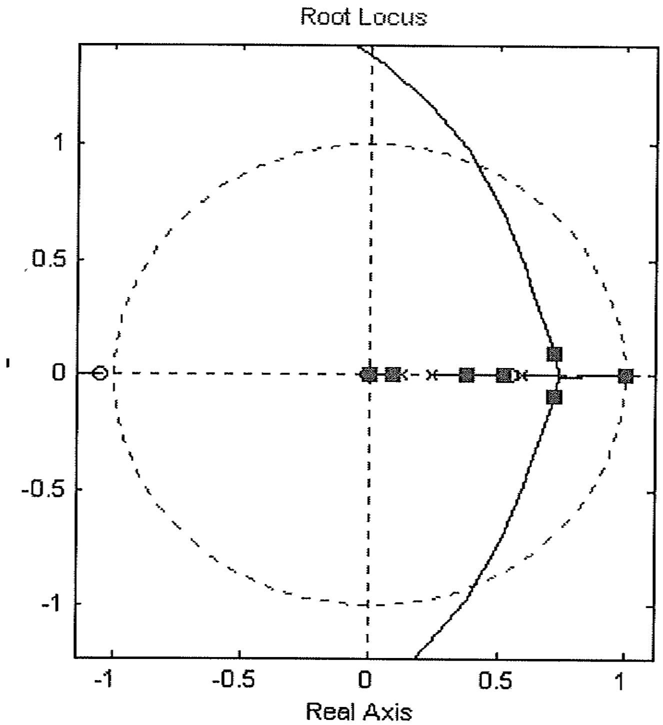
$$T^*(s) = \frac{\alpha^*(s)}{\omega^*_{req}(s)} = \frac{G^*_{PI}(s) \cdot G_{ZOH} G_{DC} G_c^*(s) \cdot n}{1 + G^*_{PI}(s) \cdot G_{ZOH} G^*_{DC}(s) \cdot n} \qquad \textbf{Eqn. 4-18}$$

Or in z domain

$$T(z) = \frac{0.002841 \cdot (z-0.546) \cdot (z-0.519) \cdot (z-1) \cdot (z+1.05) \cdot (z+0.008109) \cdot (z-1.459 \cdot 10^{-6})}{(z-1)^2 \cdot (z-0.5983) \cdot (z-0.519) \cdot (z-0.2453) \cdot (z-0.1209) \cdot (z-1.459 \cdot 10^{-6})} \qquad \textbf{Eqn. 4-19}$$

The gain K_P=18 provides fast transient response of the system and ensures that the system stays stable. The final transfer function of the closed-loop servo system is shown by Eqn. 4-20:

$$\frac{\alpha(z)}{\alpha_{req}(z)} = \frac{0.051137 \cdot (z+1.05) \cdot (z-1) \cdot (z-0.519) \cdot (z+0.008109) \cdot (z-1.459 \cdot 10^{-6})}{(z-0.08674) \cdot (z-0.3796) \cdot (z-0.519) \cdot (z-1) \cdot (z-1.459 \cdot 10^{-6}) \cdot (z^2 - 1.447 \cdot z + 0.5317)} \qquad \textbf{Eqn. 4-20}$$



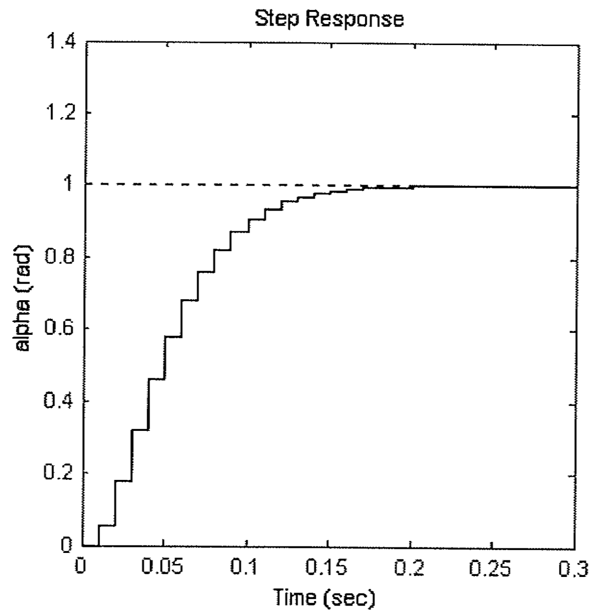


Figure 4.12 Root locus of the system

Figure 4.13 Transient response of the system

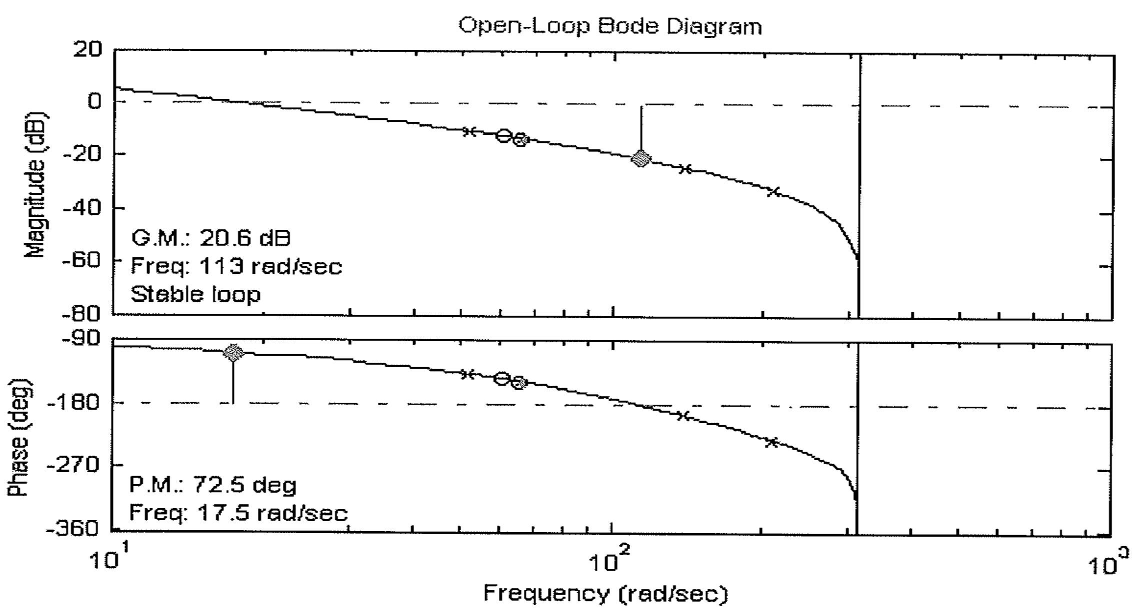


Figure 4.14 Bode plot of the leg's control system, single leg mode

The servo system of the leg with the chosen coefficients for P-PI controller is stable with a gain margin 20.6dB and a phase margin 75.5 deg., see Figure 4.14.

Dealing with the power amplifier nonlinearity

In the design of the controller, provided above, the power amplifier is considered operating in a linear region. However, under certain conditions, the amplifier may become non-linear, changing the dynamics of the system, or even making it unstable. The torque of the DC motor is proportional to the current supplied by the amplifier. In cases when the system requires high torque the DC motor will draw high current, which may exceed the maximum allowable current for this type of DC motors, causing its permanent damage. Thus, limiting the maximum allowable current will limit the maximum torque of the servo system. The robot is a mobile system with limited on-board power resources. All subsystems of the robot should function within strict voltage and current limits. Attempt to increase the power capacity will increase the cost of the system, its size and weight. The use of higher torque DC motors for the servo system will increase power consumption, the size and the weight of the robot. Increased size and weight of the robot requires the servo system to have higher torque DC motors, which, again, increase the power consumption requirements but the type of an overhead line and an obstacle restricts the size and the weight of the robot.

One of the ways to keep the system linear is to control the maximum torque of the DC motor by applying the input control signal incrementally, following a trapezoidal angular profile with a slope $K = \tan\alpha = \frac{\alpha_{req}}{t_1}$ as shown in Figure 4.15.

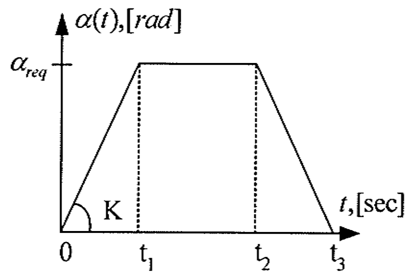


Figure 4.15 Angular position profile

The motor turns over t_1 to the required angle α_{req}, keeps the desired angle for the required time t_2 and turns back to the initial position over t_3. The slope K, if properly chosen, provides acceptable currents in the DC motor during all operational time.

Figure 4.16 shows a response of the system for K=4.16. Parameters of the DC motor for the servo system of the leg are presented in Appendix A. The maximum allowable current for the DC motor is limited by 2A and maximum voltage by 12V. In this configuration, the torque required from the system exceeds the system's ability to provide it. As a result, the amplifier saturates and causes the system to oscillate, that is not acceptable.

Figure 4.17 shows a response of the system for K=1. The required torque and provided torque are balanced and the current amplifier is not saturated. The system tracks the input signal with a delay of 0.15 sec, and provides a smooth transition from the initial angle 0 radian to the required angle 1 radian. Also, the system shows good rejection of load disturbances. At time t=2.5 sec, the external torque 1N·m was applied to the system, causing very insignificant change of the angle and fast compensation of this change. In total, the response of the system with K=1 is considered satisfactory and can be used as a final result for the control system of the leg.

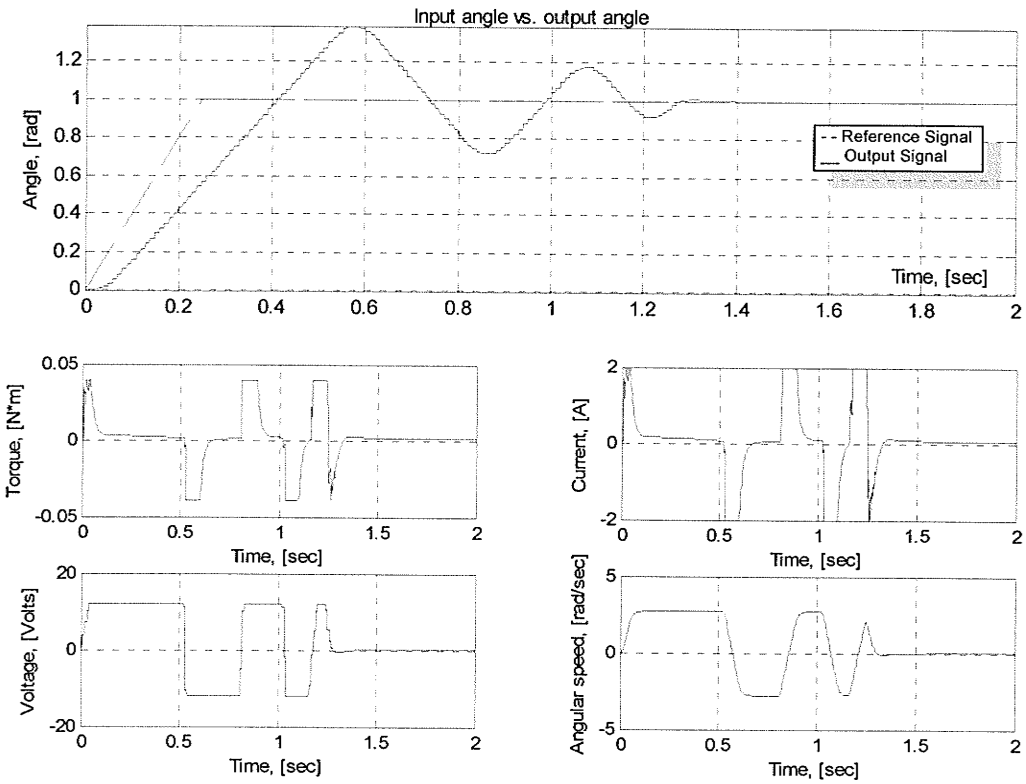


Figure 4.16 Response of the control system for K=4

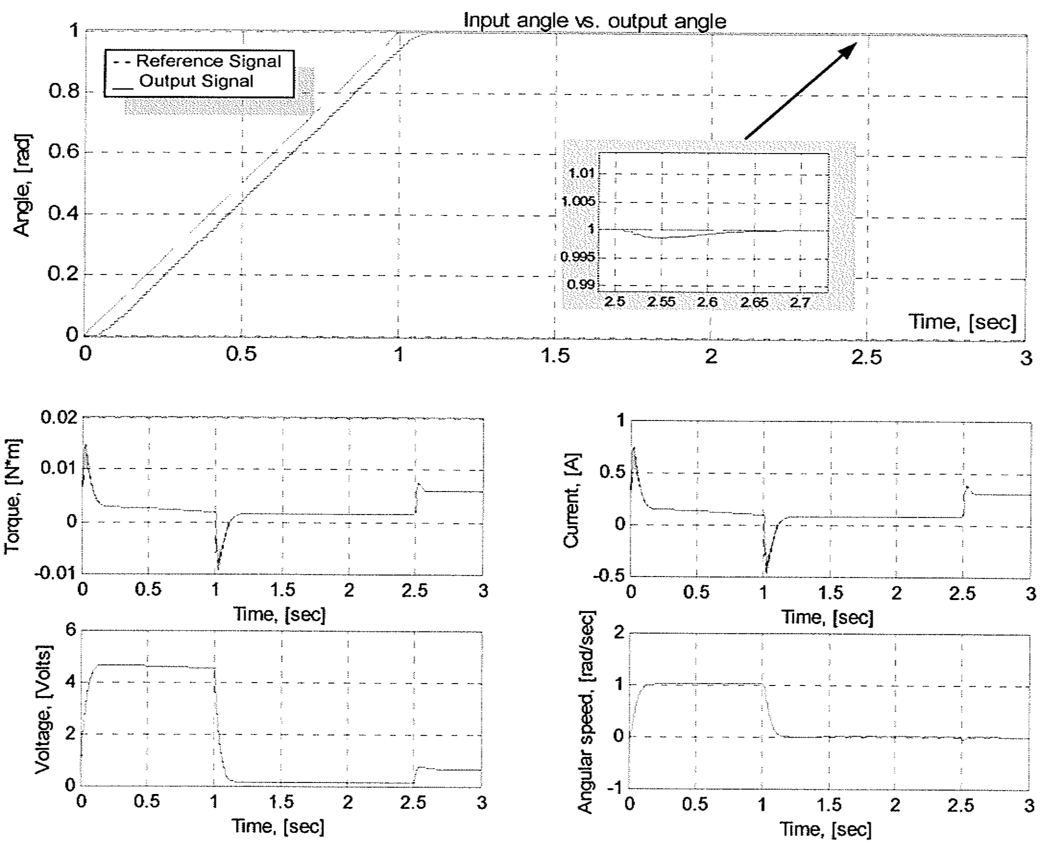
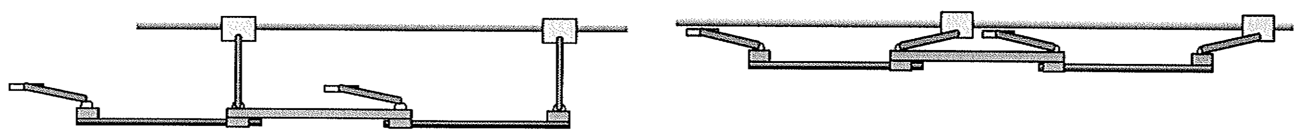


Figure 4.17 Response of the control system for K=1

4.1.2 Cooperative mode

Cooperative mode has a crucial role in the robot's motion. Due to very strict restrictions of the size, the weight, the consumed power, and the cost, and in order to perform a wide variety of maneuvers on the line, the robot should be able to combine the torque of several DC motors to produce a higher torque required for a motion. Thus, the combination of low power motors can produce the torque required for the particular motion.



a) b)

Figure 4.18 Examples of a cooperative mode:
a) Initial position of the robot,
b) Two legs cooperate in a legged locomotion

In the cooperative mode, the functional parts of the robot, which participate in a motion, move synchronously with equal angular or linear speed. There is a significant difference between controlling a single motor system and a multi-motor one. In a single motor system, the servo system has its own object of control – a leg, a gripper. A control signal sent to this system does not involve other systems. In a multi-motor system, motors become coupled and initially independent servo systems have the same object of control. Now, this object of control includes all participated independent objects of control coupled through the common media. That makes them mutually dependent on each other. Each servo system of the same type, due to tolerances in a technological process, will have slightly different parameters and as result will provide slightly different torques, and will have slightly different speeds. If the control stays the same as for an independent system, individual control for an individual object, one of the participating servo systems will outperform the other systems. Having the same reference signal, the servos will have different feedback signals. It will create the "push-pull" situation when one servo, more powerful, will push the controlled object, and the "weaker" servo will resist the change and pull the object back. Instead of cooperation the result is a counteraction. This will lead to a tremendous loss of power, mechanical misalignment and possibly the destruction of some components of the robot.

One of the possible solutions for a cooperative motion is to open control loops of individual servo systems and to introduce one, common for all participating systems, feedback. In this way, all systems will have the same error signal and each individual DC motor will produce maximum required torque, according to its designed properties, adding it to a total torque of the coupled system. In this configuration, the most powerful DC motor produces a little more torque then the weaker motor. Taking into account the simplicity of this method and a very little design overhead (e.g. mostly software), this method is appropriate for small-scale economical objects. Application of this method is suitable for equal type systems with the same type of DC motors.

4.1.2.1 Mathematical model

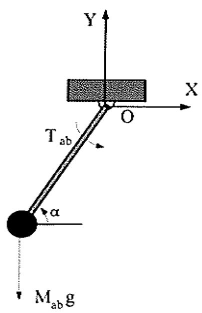


Figure 4.19 Model of leg in cooperative mode

The servo systems of the robot participating in a cooperative motion, work on the same load, so the model of the pendulum may represent the model of the legs participating in the cooperative motion.

In this mode, the grippers of a leg hold the line. The servo of the legs, applying the torque T_{ab} deflect them. The base of the robot moves in the horizontal and the vertical directions. At least two legs participate in this motion. Thus, the weight of the robot's body is distributed equally among all participating legs, in this case two legs, see **Eqn. 4-21**:

$$M_{ab} = \frac{1}{2}\left(M_r - 4 \cdot M_a\right)$$ **Eqn. 4-21**

where:

M_{ab} - mass of the robot's body to be lifted by one leg, [kg]

M_r -mass of the robot, [kg]

M_a - mass of the gripper, [kg]

The required torque T_{ab} per leg can be expressed by:

$$T_{ab} = J_{ab} \cdot \frac{d^2\alpha}{dt^2} - M_{ab} \cdot L_a \cdot g \cdot \cos\alpha(t) + M_{ab} \cdot g \cdot R_a \cdot \sin(\tan^{-1}(\mu_a)) \cdot sign(\dot{\alpha})$$ **Eqn. 4-22**

where:

$J_{ab} = M_{ab} \cdot L^2{}_a$ - moment of inertia of the robot per leg, participating in motion [kg·m^2]

The equation of motion of a coupled DC motor system can be found from the equation of balance of energies:

$$T_1 \cdot \omega_1 + T_2 \cdot \omega_2 = \frac{dW_k}{dt} + T_L \cdot \omega + B_{m1} \cdot \omega_1^2 + B_{m2} \cdot \omega_2^2 \qquad \textbf{Eqn. 4-23}$$

where:

$W_k = \frac{J_1 \omega_1^2}{2} + \frac{J_2 \omega_2^2}{2} + \frac{J_{a1} \cdot \omega^2}{2} + \frac{J_{a2} \cdot \omega^2}{2}$ is a kinetic energy of rotating parts of coupled DC motors.

ω_1, ω_2 - angular speed of an individual DC motor, [rad/sec]

B_{m1}, B_{m2} - viscous friction coefficient of an individual DC motor, [N·m/(rad/s)],

T_1, T_2 - torque of an individual DC motor, [N·m]

J_1, J_2 - rotor inertia of an individual DC motor, [kg·m^2]

J_{a1}, J_{a2} - moment of inertia of a leg participating in a coupled motion, [kg·m^2]

After differentiation, take a notice that the angular speed of a load is the same for both DC motors $\omega = \omega_1 \cdot n = \omega_2 \cdot n$,

then

$$T_1 \cdot \frac{\omega}{n} + T_2 \cdot \frac{\omega}{n} - T_L \cdot \omega = J_{m1} \cdot \frac{1}{n^2} \cdot \frac{d\omega}{dt} + J_{m2} \cdot \frac{1}{n^2} \cdot \frac{d\omega}{dt} + J_{a1} \cdot \frac{d\omega}{dt} + J_{a2} \cdot \frac{d\omega}{dt} + B_{m1} \cdot \omega_1^2 + B_{m2} \cdot \omega_2^2 \qquad \textbf{Eqn. 4-24}$$

The angular speed of a coupled system before the gear box is

$$\omega_{DC} = \frac{1}{n} \cdot \omega \qquad \textbf{Eqn. 4-25}$$

$$T_1 + T_2 - n \cdot T_L = (J_{m1} + J_{m2} + n^2 \cdot J_{a1} + n^2 \cdot J_{a2}) \cdot \omega_{DC} \cdot s + B_{m1} \cdot \omega_{DC} + B_{m2} \cdot \omega_{DC} \qquad \textbf{Eqn. 4-26}$$

The motors participating in a cooperative motion are of the same type. Thus, it is considered that parameters of motors are approximately the same:

$B_{m1} = B_{m2}$

and

$J_{a1} = J_{a2}$

The final equation the coupled DC motor system can be expressed by Eqn. 4-27

$$T_1 + T_2 - n \cdot T_L = (J_{m1} + J_{m2} + 2 \cdot n^2 \cdot J_{a1}) \cdot \omega_{DC} \cdot s + 2 \cdot B_m \cdot \omega_{DC} \qquad \textbf{Eqn. 4-27}$$

The equivalent DC motor system is presented in Figure 4.20.

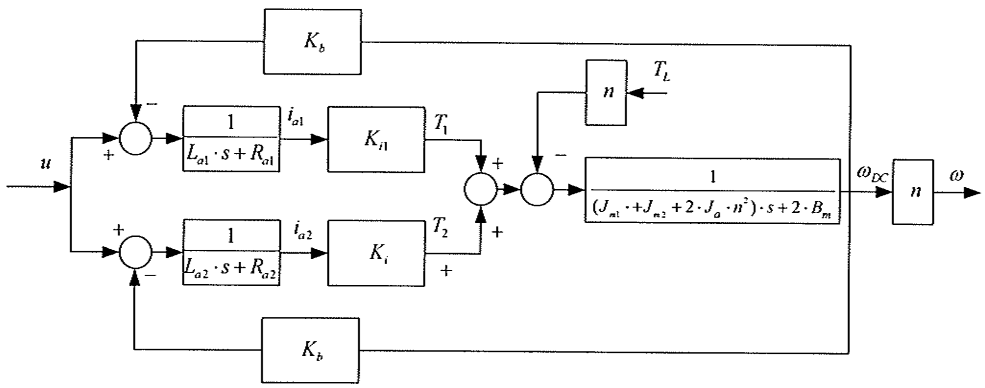


Figure 4.20 Two DC motor system working on a common load

The response of the system to change of the leg's angle from α=π/2 to 0 is shown in Figure 4.21. As the angle α changes, the distance between the body of the robot and the overhead wire reduces. The robot advances in a horizontal direction at a distance approximately equal to the length of a leg. As follow from Figure 4.21 the system tracks the reference signal with a delay of 0.1 sec without distortions. Noise rejection of a 1N·m external torque is effective and the current from the amplifier does not exceed limits.

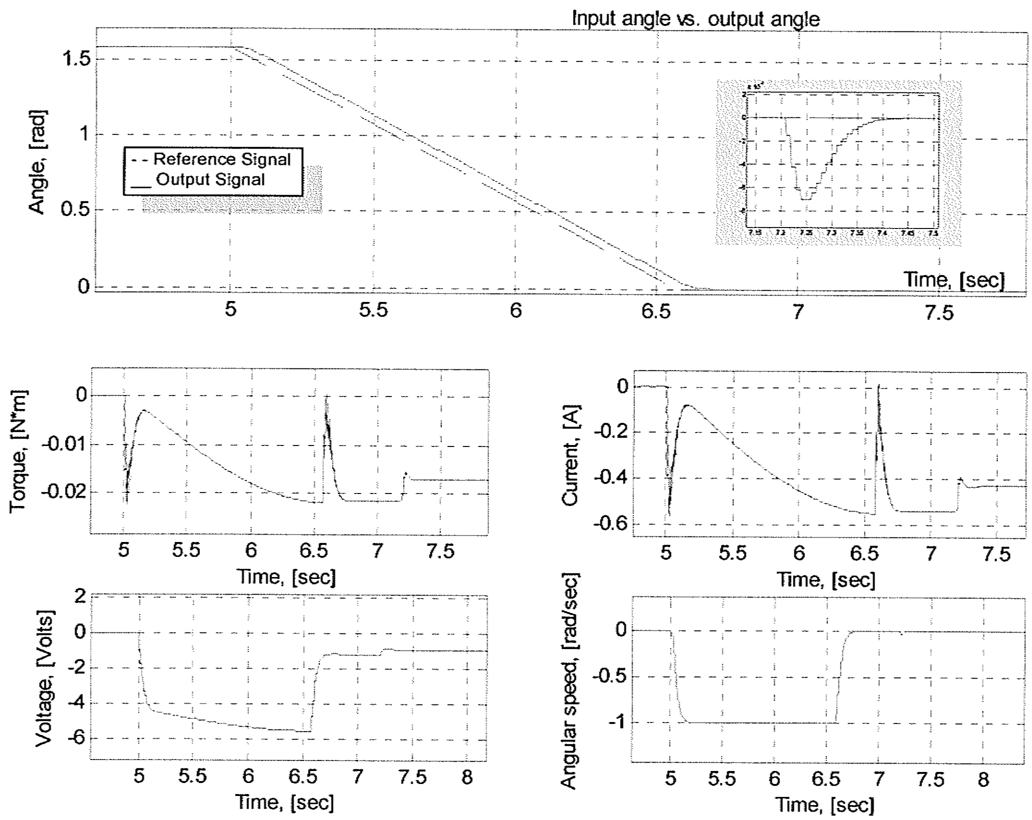


Figure 4.21 Response of a coupled DC motor system for K=1

4.2 Control system of grippers

4.2.1 Mathematical model

The assembly of an actuator, a rod with a lead screw, a load and a system of levers may represent the model of a gripper. The actuator rotates the rod, and the lead screw converts the rotational motion of the rod into a translational motion of the load. Moving load transmits this motion to the levers, which grasp the overhead line by taking the state "Closed", or releases the line by going into the state "Opened".

Transmission ratio from the load to the levers is 1:1. The friction in the grasping levers is small and can be neglected. The force acting on the load is fully transmitted to the grasping levels. So, the model of the gripper can be simplified by elimination of the levers from the model. This model is shown in Figure 4.23.

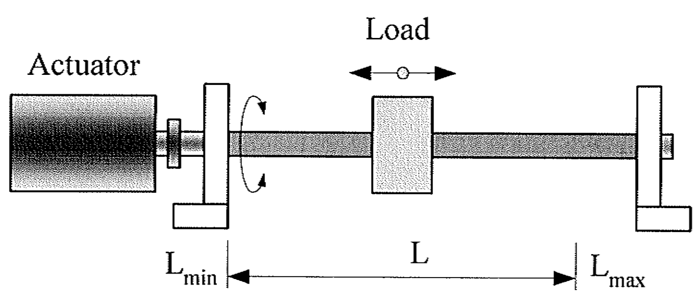


Figure 4.23 Model of the gripper

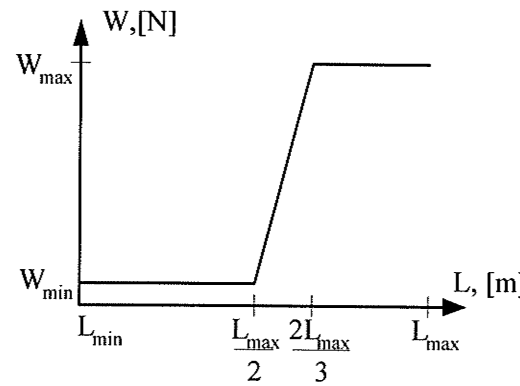


Figure 4.22 Distribution of grasping force

The force profile required for secure grasping and holding the line, is presented in Figure 4.22. On the interval from L_{min} to $L_{max}/2$, the gripper doesn't have a contact with the wire and the servo system of the gripper is required to provide the minimum force for overcoming the friction in the assembly of the gripper. At point $L_{max}/2$, the gripper touches the line and starts squeezing it. The force required for holding the line is W_{max} and it is reached at the point $2L_{max}/3$. Further motion of the load secures the line in the gripper. The expression for the required force W has the following form:

$$W(l) = \begin{cases} W_{\min}, 0 \le l \le \frac{1}{2} \cdot L_{\max} \\ W_{\min} + (l - \frac{L_{\max}}{2}) \cdot \tan\gamma, \frac{1}{2} \cdot L_{\max} < l \le \frac{2}{3} \cdot L_{\max} \\ W_{\max}, l \ge \frac{2}{3} \cdot L_{\max} \end{cases} \qquad \textbf{Eqn. 4-28}$$

where:

$\tan\gamma = \dfrac{W_{\max} - W_{\min}}{\frac{2}{3}\cdot L_{\max} - \frac{1}{2}\cdot L_{\max}}$, is the slope on the interval $1/2L_{max}$ to $2/3L_{max}$

$W_{\max} = \dfrac{M_r \cdot g}{2}$, maximum force required for holding the wire, [N]. It is equal to the half of robot's weight

M_r – mass of the robot, [kg]

Major factors which contribute to the required actuator torque consist of the following components:

- *Dry friction* (Coulomb friction) of the lead screw and the load. It can be expressed as the following:

$$T_{lead} = W(l)\cdot r_g \cdot sign(\omega_g)\cdot \tan(\Theta + sign(\omega_g \cdot \Phi_k)) \qquad \textbf{Eqn. 4-29}$$

where:

$W(l)$ – force required for holding the wire, as a function of distance.

r_g – the mean radius of a threat, [m]

Θ - lead angle, [rad]

ω_g – angle speed of the lead screw, [rad/sec]

Φ_k – kinetic angle of friction, and $\Phi_k=\tan^{-1}(\mu_k)$

μ_k – coefficient of kinetic friction, [-]

- *Moment of load inertia.* For the moving load on the lead screw [BKuo91], the moment of inertia is equal to:

$$J_g = \frac{W(l)}{g}\cdot\left(\frac{L_g}{2\cdot\pi}\right)^2 \qquad \textbf{Eqn. 4-30}$$

where:

L_g - is the screw of the lead, [m]

Thus the total actuator torque for the gripper:

$$T_{lead} = W(l)\cdot r_g \cdot sign(\omega_g)\cdot \tan(\Theta + sign(\omega_g \cdot \Phi_k)) + \frac{W(l)}{g}\cdot\left(\frac{Lg}{2\cdot\pi}\right)^2\cdot\frac{d\omega}{dt} \qquad \textbf{Eqn. 4-31}$$

4.2.2 Design of the controller

An equivalent block diagram (Figure 4.24) presents the control system of the gripper. This system tracks the desired position of the load on the lead screw. Depending on the position of the load, the gripper transitions to different states. The state of the gripper is not limited by boundary states (i.e., "Open" or "Closed"); it can also take medium transitional states, like "Half open", that can be advantageous for some types of maneuvers. For example, in a legged locomotion when a gripper is required to be only in a "Closed" or a "Half Open" state.

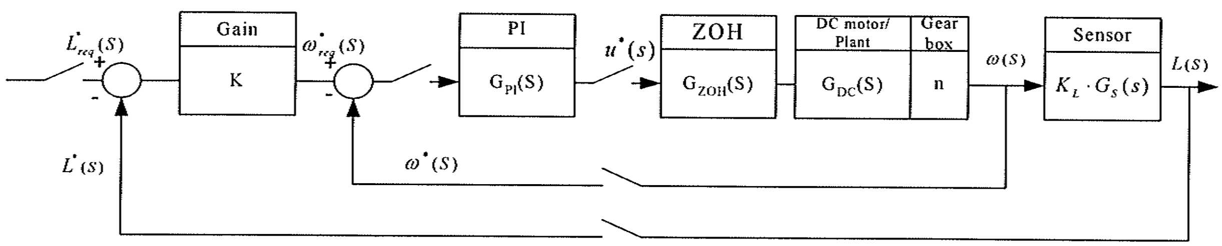


Figure 4.24 Control system of a gripper

The transfer functions of the system closed loop system is expressed by Eqn. 4-32

$$\frac{L(z)}{L_{req}(z)} = \frac{0.084484 \cdot z \cdot (z+1.025) \cdot (z-1) \cdot (z-0.618) \cdot (z-0.616) \cdot (z+0.003993)}{z \cdot (z-1) \cdot (z-0.616) \cdot (z-0.5295) \cdot (z-0.08666) \cdot (z^2 - 1.229 \cdot z + 0.3813)} \quad \textbf{Eqn. 4-32}$$

Coefficients of the Proportional-Proportional-Integral controller found from the root locus are tuned to provide an acceptable stability and smoothness of the output response of the system, (see Figure 4.25). Special care is taken to eliminate oscillations from the transient response.

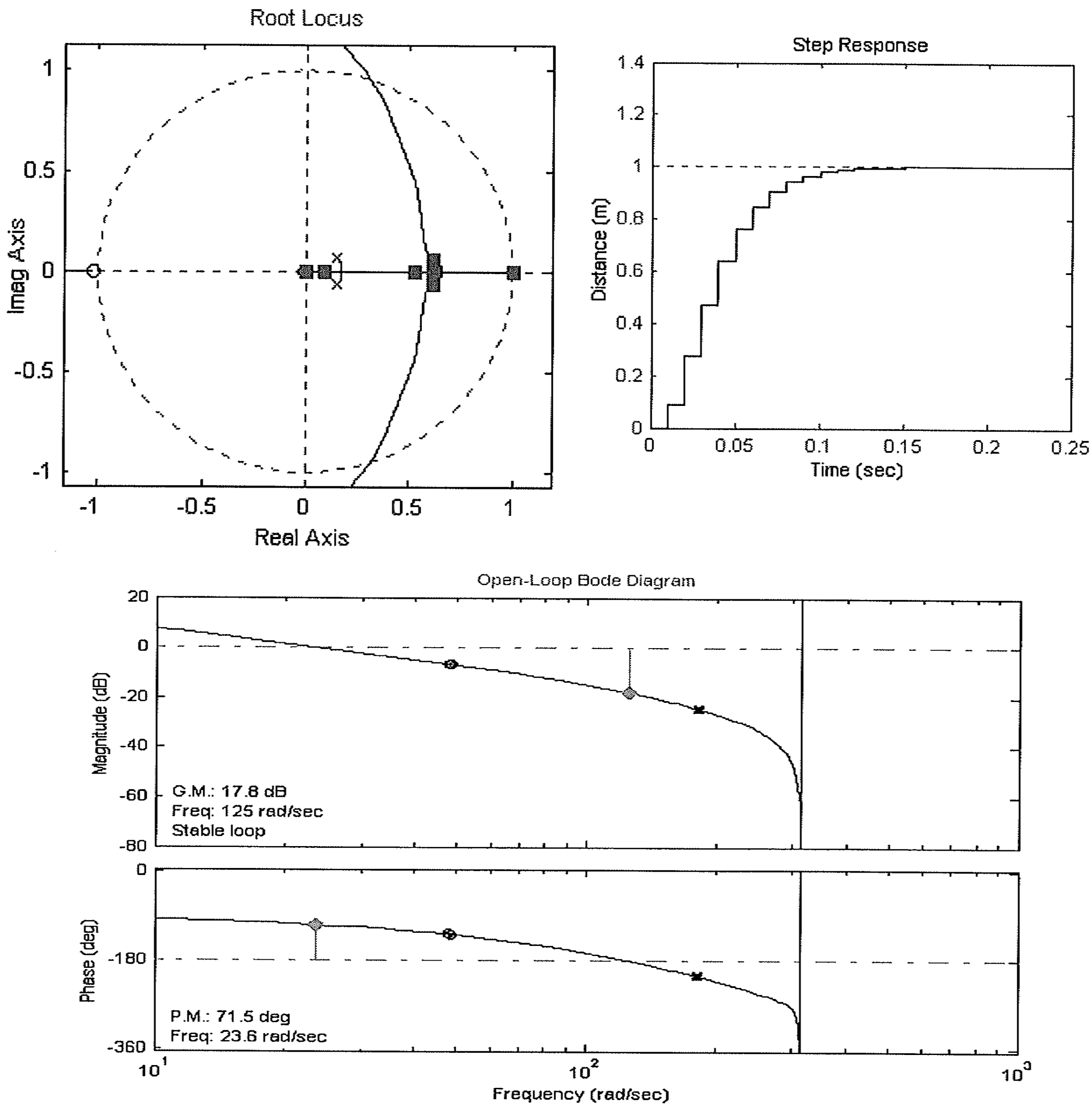


Figure 4.25 Root locus and Bode diagram for design of the controller of the gripper

The response of the control system of the gripper, presented in Appendix A.3, is shown in Figure 4.26. As seen from the figure, proportional coefficients K=190000 and K_p=0.1, K_I=0.063 of the PI controller for the sampling time T=0.01 sec provide the system with a stable response and a minimum delay of 0.12 sec from the reference signal. The consumed current, the peak torque and the continuous torque of the DC motor also stay within the required limits for this type of motors. It takes the gripper 3 sec. to transit from the state "Open" to the state "Closed".

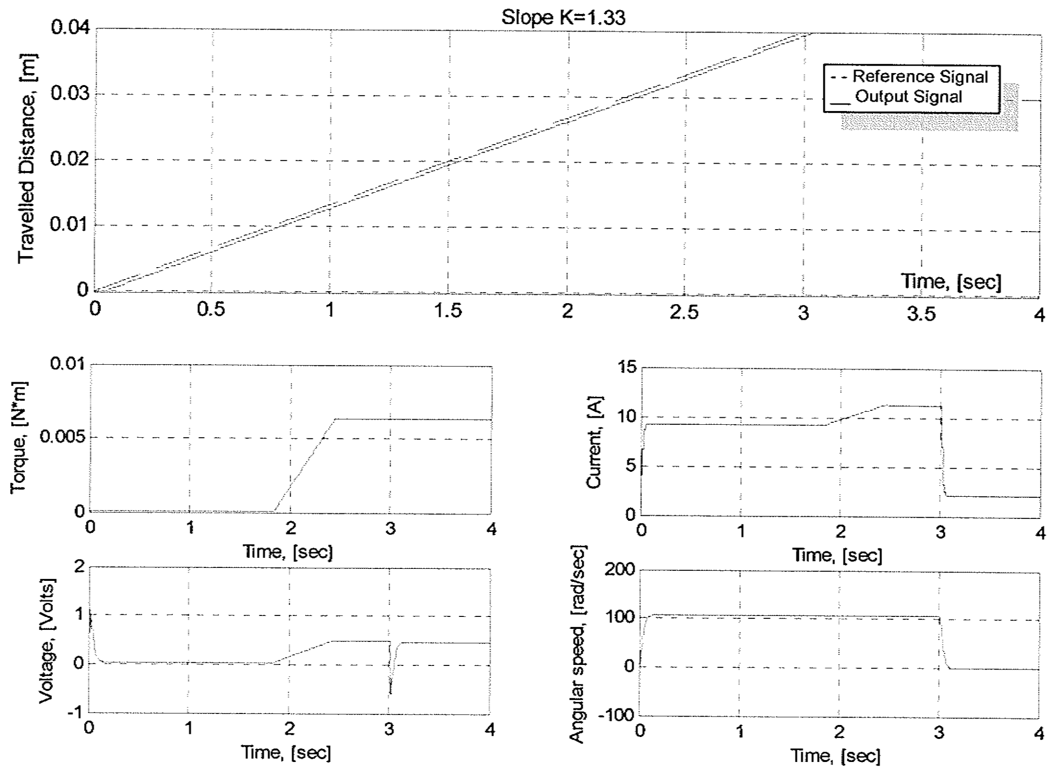


Figure 4.26 Response of the gripper's control system for K=1.33

4.3 Control system of a drive unit

Every gripper of the robot is equipped with one driving wheel located on the grasping levers. When the servo system applies the torque to this wheel, the robot performs a translational motion along the overhead line. During this motion, there are two control parameters – the speed of the motion and the traveled distance of the robot. For long-range travels, the robot needs to control the speed only. Once the proximity sensors have detected an obstacle in the robot's way, the control system switches to control the distance. Since that moment, the robot approaches the obstacle, prepares to avoid the obstacle, and then avoids the obstacle under the supervision of the distance controller.

4.3.1 Mathematical model

Figure 4.27 shows the model of the drive wheel of the driving unit. The wheel is supported by two radial bearings. For maintaining the motion, the torque actuator should overcome the frictional resistance in the bearings and the moment of inertia of the robot.

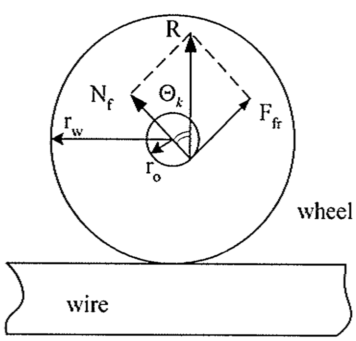


Figure 4.27 Model of the drive wheel

The final expression for the required torque of the servo system of the driving wheel is

$$T_o = J_o \cdot \frac{d\omega_o}{dt} + F_o \cdot r_o \cdot \mu_k \cdot sign(\omega_o)$$ **Eqn. 4-33**

where:

To – torque of driving wheel, [$N \cdot m$]

$J_o = m_o \cdot r_w^2$ - moment of inertia, [$kg \cdot m^2$]

r_o – radius of the axle, [m]

r_w – radius of the wheel, [m]

ω_o – angular speed of the wheel, [rad/sec^2]

N_f – normal force [N]

R – reaction of the bearing [N]

Θ_k – angle of friction [rad]

$\mu_k = \tan(\Theta_k)$ - kinematic coefficient of friction, for small values of the angle of friction Θ_k, $\sin(\Theta_k) \approx \tan(\Theta_k)$

F_o – grasping force [N]

The Grasping force F_o depends on how many wheels the configuration of the robot participate in the motion – 2 drive wheels or 4 drive wheel, and can be approximated as the following:

$$F_o = \begin{cases} \frac{m_R}{2} + \frac{m_R}{4} & \text{- for 2 driving wheels} \\ \frac{m_R}{4} + \frac{m_R}{4} & \text{- for 4 driving wheels} \end{cases}$$ **Eqn. 4-34**

Where:

$\frac{m_R}{2}$ and $\frac{m_R}{4}$ are masses,[kg]

4.3.2 Controller of a distance

The Proportional-Proportional-Integral (P-PI) control system of a distance for the driving unit is shown in Figure 4.28. The output shaft of the DC motor is connected to the integrating sensor. Its output is compared with the reference signal. When the error signal becomes zero, the system has advanced at the required distance L_{dreq}. The motion of the robot should exclude oscillation, and be smooth and precise.

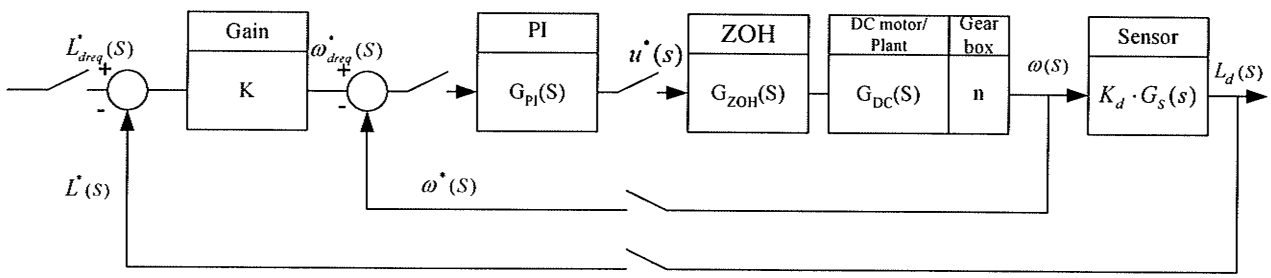


Figure 4.28 Controller of distance for driving unit

The transfer function of the closed loop system of the driving unit has the following form:

$$\frac{L_d(z)}{L_{req}(z)} = \frac{0.028544\cdot(z+1.18)\cdot(z-1)\cdot(z-0.959)\cdot(z-0.959)\cdot(z-0.9589)\cdot(z+0.004405)}{(z-1)\cdot(z-0.959)\cdot(z-0.9589)\cdot(z-0.03585)\cdot(z^2 - 1.52\cdot z + 0.5843)} \quad \textbf{Eqn. 4-35}$$

Where:

The time sampling = 0.01 sec

K = 1430 – proportional coefficient

K_P = 0.8919 – proportional coefficient of the PI controller

K_I = 0.03813 – integral coefficient of the PI controller

Coefficients of the system were obtained from the root locus, shown in Figure 4.29, by pole placement method. The coefficients provide stable and fast response of the DC motor without oscillations.

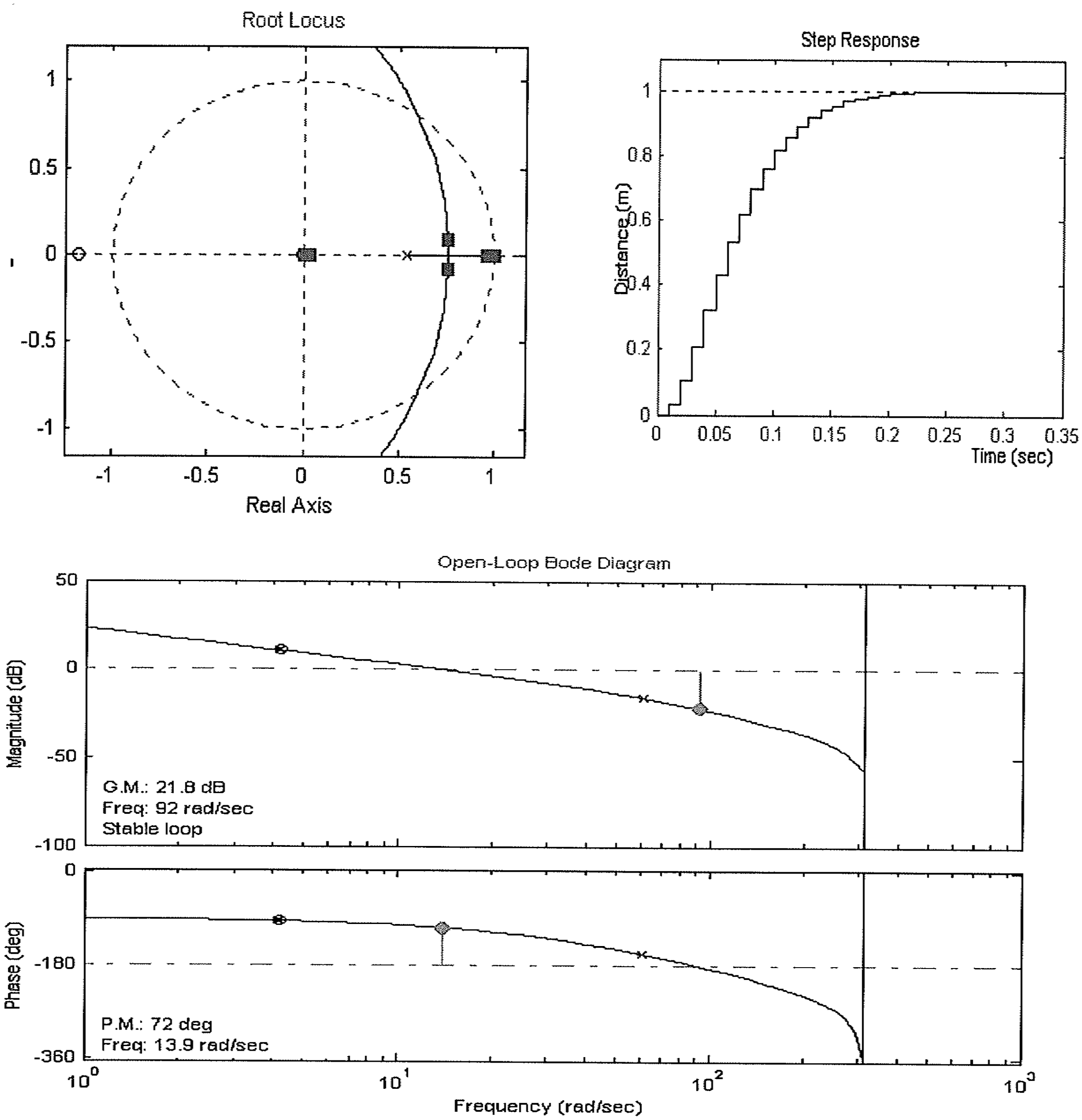


Figure 4.29 Root locus and Bode diagram for design of the controller of the drive unit

A simulation of the servo system shown in Appendix A.4 verifies results of the design for a 2-wheel configuration of the robot. As seen from Figure 4.30, the system tracks a reference signal, which specifies the required traveled distance, with a delay of 0.1 sec. Load disturbance rejection of the system is capable to reject the 0.1 N·m external torque without noticeable change in the position of the robot. The robot has a significant inertia, but despite this the servo system stays within strict limits on input current for the DC motor, providing the required peak torque for the system.

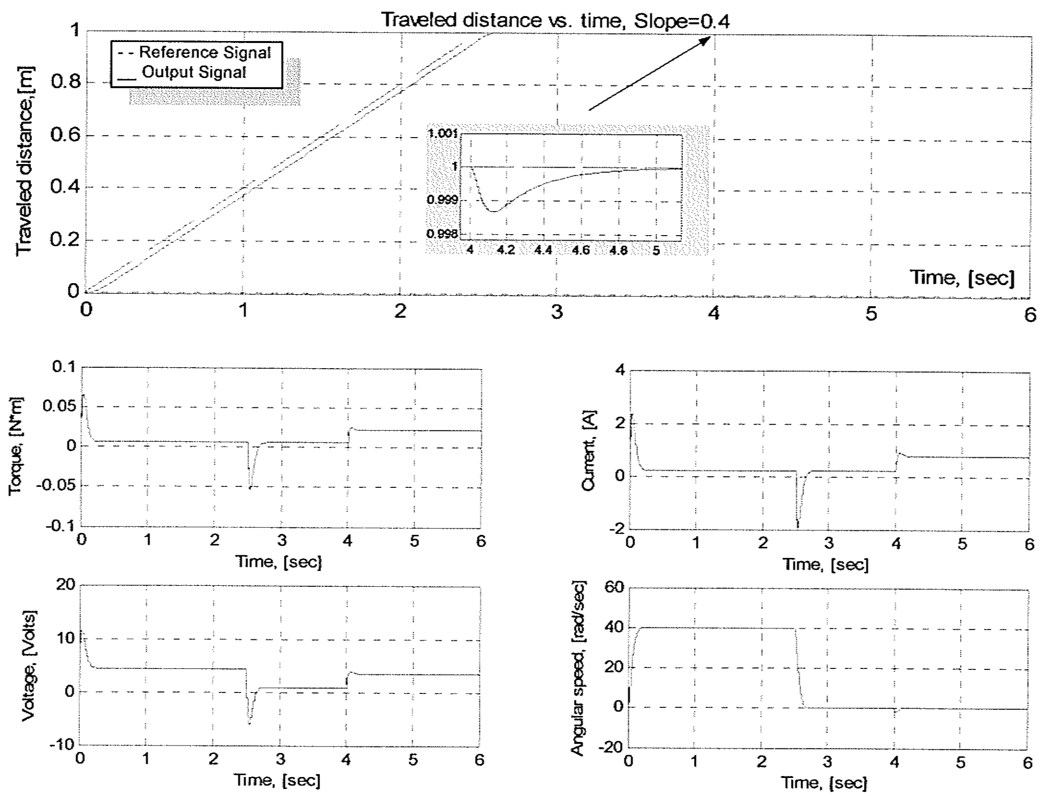


Figure 4.30 Response of the distance control system of a drive unit

4.3.3 Controller of a velocity

The inner control loop of the distance controller is used as a controller of a velocity for the drive unit, see Figure 4.31.

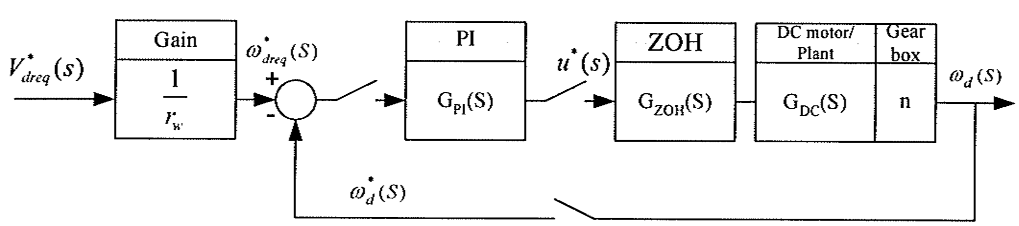


Figure 4.31Control loop of velocity control system of a drive unit

The velocity controller has one additional gain, which converts a desired linear speed of the robot into a desired angular speed of the driving wheel, and expressed by Eqn. 4-36

$$\omega_{dreq}(t) = \frac{V_{dreq}(t)}{r_w} \qquad \textbf{Eqn. 4-36}$$

The results of simulation of the servo system, presented in Appendix A.5, are shown in Figure 4.32. Taking into account the total weight of the robot of 5 kg, and that only 2 wheels are used for the motion, the system shows a good speed performance, accelerating the robot from 0 m/sec to 1 m/sec in 2.5 sec. At the same time the peak and the continuous torques of the DC motor stay within the specified limits. The output current of the amplifier also does not reach its saturation level, providing a linear response of the system.

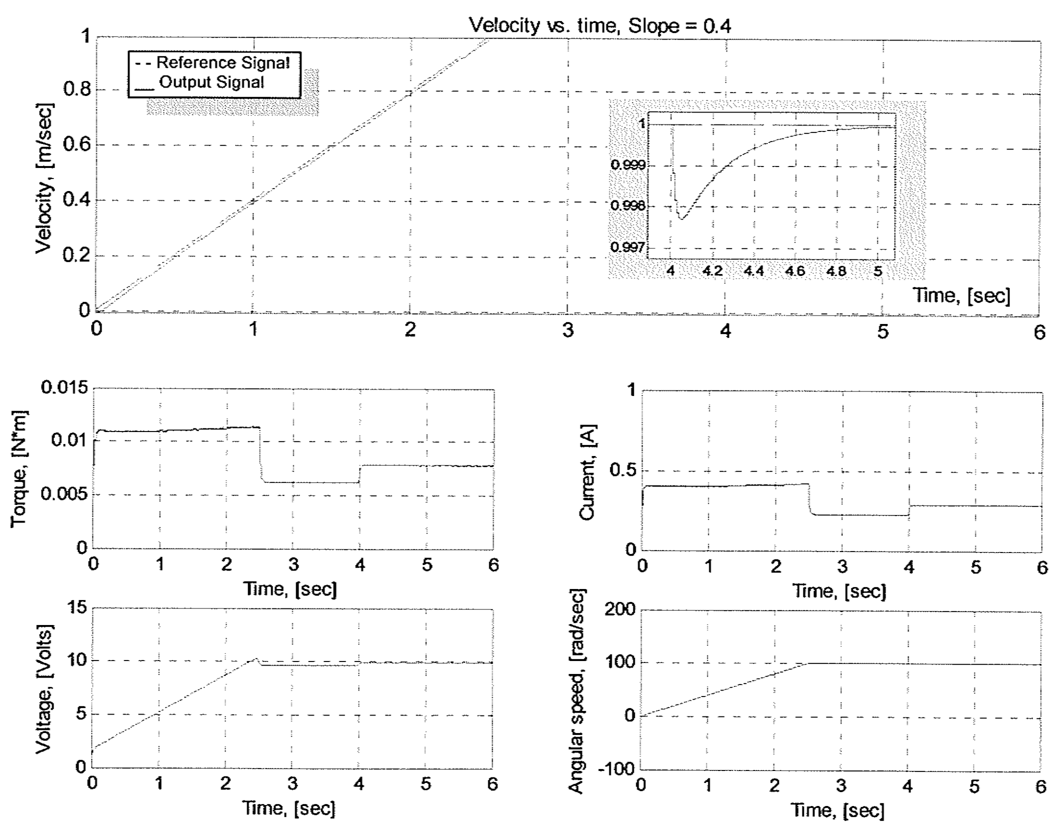
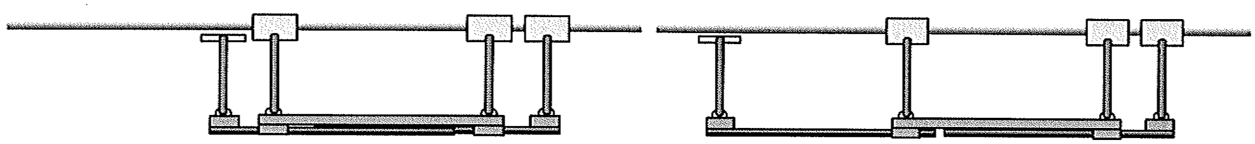


Figure 4.32 Response of the speed control system of a drive unit

4.4 *Design of a controller for base extensions*

The base extensions of the robot provide essential means for the robot's motion. Being extracted, they allow the robot to extend its length and go beyond the obstacle. The base extensions can participate in two types of motion. The first one is shown in Figure 4.33. The robot extracts and retracts one base extension. Only the servo drive of that base extension is involved in the motion.



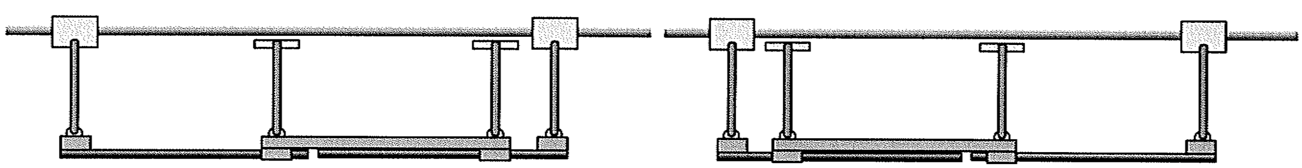
a) b)

Figure 4.33 Motion of a base extension

a) initial positon.

b) base extension extended at length L

The second motion is shown in Figure 4.34 and involves in the motion the servo drives of both base extensions. In order to synchronize the motion and prevent the "push-pull" situation, the servo systems work in a cooperative mode.



a) b)

Figure 4.34 Cooperative motion of base extensions

a) initial position

b) base of the robot moves from right end position to the left end position

For both motions, the servo systems control the traveled distance of the base extension. The servo system for a distance control is shown in Figure 4.35.

The control system of a base extension is similar to the control system of the driving unit. They use the same type of motors and a cooperative motion of 2 driving units is similar to a cooperative motion of the base extensions. The control system of the base extensions in a cooperative mode has the same coefficients for the P-PI controller.

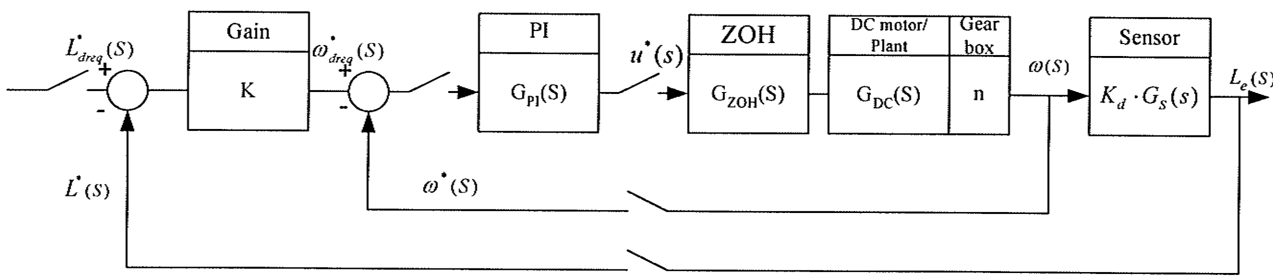


Figure 4.35 Controller of a distance for a base extension

The control system for a single base extension motion has slightly different parameters and its transfer function can be expressed by Eqn. 4-37:

$$\frac{L_e(z)}{L_{req}(z)} = \frac{0.054412 \cdot z \cdot (z+1.161) \cdot (z-1) \cdot (z-0.912) \cdot (z-0.9113) \cdot (z+0.004358)}{z \cdot (z-1) \cdot (z-0.9119) \cdot (z-0.9113) \cdot (z-0.6855) \cdot (z-0.596) \cdot (z-0.07123)} \quad \textbf{Eqn. 4-37}$$

Where

The time sampling = 0.01 sec

K = 1900 – proportional coefficient

K_P = 0.3938 – proportional coefficient of the PI controller

K_I = 0.0655 – integral coefficient of the PI controller

For selected coefficient of the P-PI controller the system has a response shown in Figure 4.36

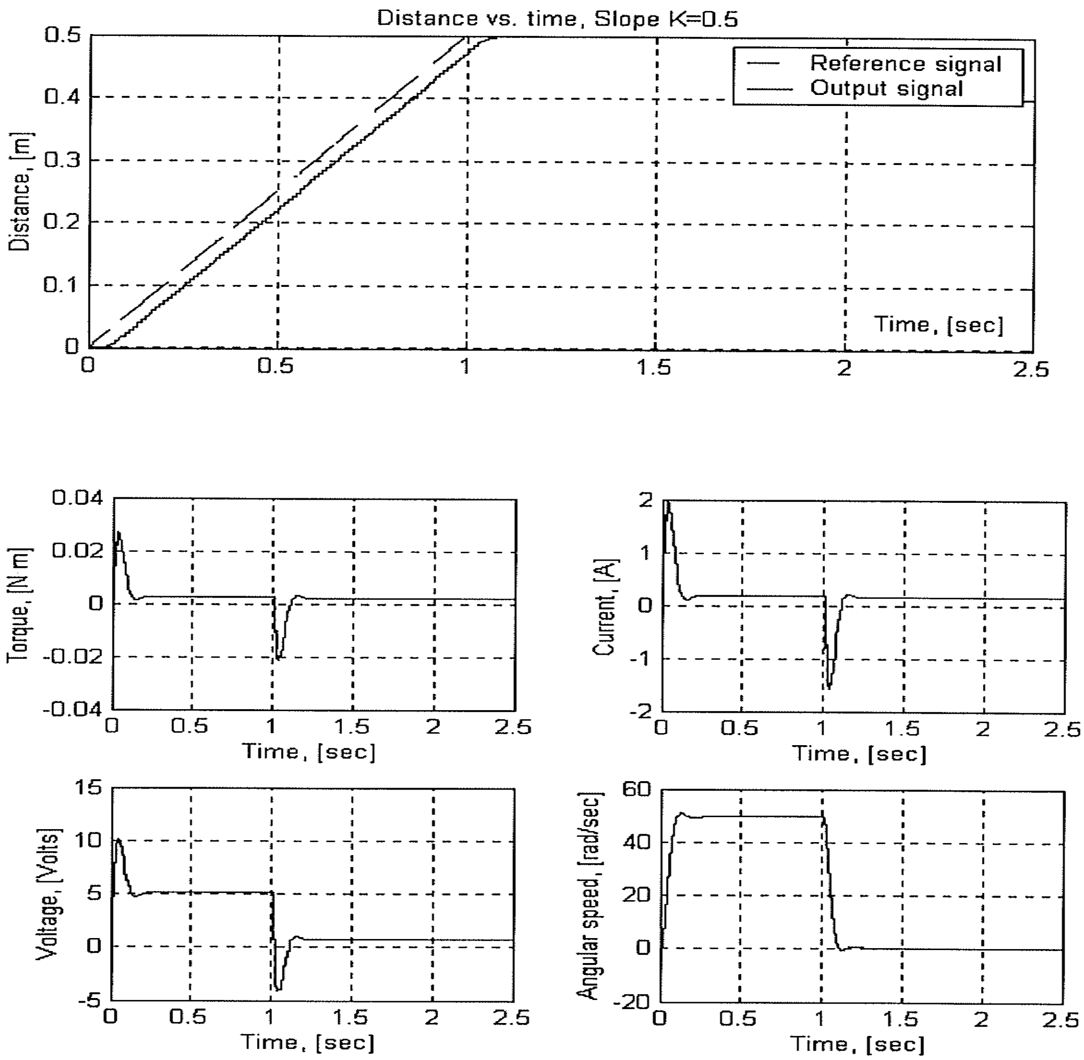


Figure 4.36 Response of the servo drive of a single base extension

5 Behavior-based control

5.1 Low level behaviors

A low level behavior accepts a control signal from a higher level behavior and produces a control signal which will be accepted by a lower level feedback controller as a required value for tracking by a servo system. In this sense, the behaviors at low level represent pure reactive control - without complex computation involved, the behaviors just pass the predetermined value of the control signal to the selected servo system. The low-level behaviors can be decoded according the Table 5.1.

Table 5.1 Low level behavior decoding

Low behavior name	Output value	Description
Grab a Line	$L_{req} = L_{max}$	Forces a selected gripper grab a line
Release a Line	$L_{req} = L_{min}$	Forces a selected gripper release a line
Drive forward, speed	$L_{dreq} = Speed$	Forces a selected drive unit to drive forward with a selected speed
Drive back, speed	$L_{dreq} = -Speed$	Forces a selected drive unit to drive back with a selected speed
Drive forward, distance	$L_{dreq} = Distance$	Forces a selected drive unit to advance the robot in forward direction on a selected distance
Drive back, distance	$L_{dreq} = -Distance$	Forces a selected drive unit to advance the robot in back direction on a selected distance
Set Leg 10 degrees	$\alpha_{req} = 10deg$	Deflects a selected leg to a 10 degree angle
Set Leg 90 degrees	$\alpha_{req} = 90deg$	Deflects a selected leg to a 90 degree angle
Set Leg 170 degrees	$\alpha_{req} = 170deg$	Deflects a selected leg to a 170 degree angle
Extension, Max	$L_{ereq} = L_{max}$	Extends a selected extension to a maximum position
Extension, Min	$L_{ereq} = L_{min}$	Extends a selected extension to a minimum position

The low-level behaviors also control end reports to the higher level behavior, which requested the action, about the results of operations in the form of the following states -"In action" or - "Not in action". The higher level behavior can synchronize its actions with the speed of the servo system just checking the states of low level behaviors. This simple mechanism releases the higher level behavior from checking the sensor information and spending time acquiring it.

5.2 *High-level behaviors*

The high-level behaviors take higher position in the hierarchy of the control system because of the complexity of algorithms involved in the generation of actions and the amount of system recourses required for the action. Mostly, the behaviors at this level consist of sets of coordinated collections of behaviors or assemblages. These collections contain a number of behaviors of different levels of the control hierarchy and reflect the sequence of actions required in order to produce the desired response.

5.2.1 Wait

This behavior is a silent behavior. It postpones all activity of the robot. But at the same time the control system still gathers data from sensors and analyzes the situation around. The condition for issuing this behavior is when the deliberative Mission Planner just needs time for making next decision. This behavior is economical. All nonessential subsystems of the robot shut down in order to preserve valuable power resources. The behavior "Wait" is different from the behavior "Emergent stop". The "Wait" is not a possible transition to following behavior as is the "Emergent stop".

5.2.2 Emergent Stop

This behavior stops the mechanical motion of the robot or its parts. This action takes place when the robot needs to stop its motion or the motion of its parts. Normally, all behaviors required to avoid this type of behavior as it is considered for some exceptional situations only. Once stopped, the system stays fully functional and ready for the next command. The source of issuing this behavior is determined and the analysis of the situation performed by the Mission Planner.

5.2.3 Obstacle Sensing and Detection

This behavior is activated when the robot moves along the transmission line. The algorithm of detection of the obstacle is active all the time. It allows detection of the presence of the obstacle on the way of the robot. The detection part of the behavior informs the robot about the obstacle and issue the states "Obstacle Detected" or "Obstacle not Detected". Once the robot encounters the obstacle, it activates the sensing part of the behavior. Sensing of the obstacle includes measuring the distance between the body of the robot and the obstacle. The behavior senses the distance between the closest leg, which is in a vertical (90 degrees) position, and the obstacle. Meanwhile, for the legs in 10 or 170 degree positions, the behavior continues to operate in the detection mode. In this way, the control system is provided with the information about the distance to the obstacle; using the legs in the minimum of the maximum angle positions determines the length of the obstacle (see Figure 2.14).

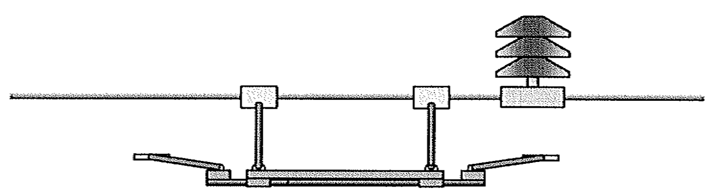


Figure 5.1 Sensing of the obstacle

Once the leg is declined from the vertical position to a min/max position, the behavior switches the sensing of the obstacle from this leg to the next leg which is vertical and is closest to the obstacle on the way of the robot toward the obstacle.

5.2.4 Approach Obstacle

As the robot detects the obstacle, the robot switches to sensing the obstacle in order to select the closest possible position to the obstacle. In this mode, the robot approaches the obstacle at a distance required for providing the space for maneuvers of the legs.

5.2.5 Back up Obstacle

This behavior is activated when the obstacle avoiding maneuver does not work for some reason. Staying very close to an obstacle may cause some possible damages to the robot or a payload from collision of the robot or its payload with the obstacle. The Back up Obstacle behavior moves the robot to a safe distance from the obstacle and surrounding objects.

5.2.6 Communication

This behavior is independent from other behaviors in the sense that it doesn't control the motion of the robot directly. But it provides the robot with information and sends the required data back. During the initialization phase, the behavior gets the information about communication schedule, amount and type of data to be received and transmitted from the Mission Planner. Then the behavior operates independently.

5.2.7 Recover

When the control system of the robot encounters problems with the hardware, the software or the failures of the mechanical system, the Mission Planner tries to compensate for this problem by reconfiguring the system, choosing different types of motion or switching to a backup subsystem. But, if the failure is persistent and does not allow the robot to perform the mission the robot has two choices. The first one is to find the safe place on the wire where the robot can wait for a maintenance team or, the second, if the maintenance team has arrived, move on the center of the line between towers, and on the command from the operator, open all grippers. By performing this behavior, the robot falls in the net set up by the maintenance team. This behavior is heavily dependent on the communication. Once this behavior is activated, the robot informs about its location and the problem to the command center.

5.2.8 Reduce Clearance

The robot's ability of reduction of clearance between the robot's base and the overhead line is very critical for some missions. This behavior approaches the payload, which is attached to the base of the robot, closer to the wire. Another application for this behavior is reduction of a sail area of the robot. This behavior also activates, when the system detects the wind above the recommended values. Approaching the wire, the robot significantly reduces the impact of forces from the blowing wind and has better chances to stay vertical.

5.2.9 Move

This motion provides the robot with different types of motion. Selection of the appropriate type of motion depends entirely on the Mission Planner according to the priorities of different types of motions. Priorities for motions are based on the energy efficiency of a specified motion. Thus, the Wheeled motion is the most economical motion and has the highest priority. Next efficient motions are Earth-worm like motions. And the less efficient motion is legged locomotion. The "Move" motion is called every time when the robot needs to move in either direction.

5.2.10 Obstacle avoidance

The synchronization of the legs, the grippers, the base extensions and the motions during the obstacle avoiding algorithms entirely depends on this behavior. The type of the obstacle is determined by the "Obstacle Detection & Sensing" behavior. According to the type of the obstacle, the Planner confirms the preferred type of obstacle avoidance which is then implemented by the "Obstacle Avoidance" algorithm.

5.2.11 Fault Detection

The constant monitoring of health of the functional components and the subsystems of the robot is a prime duty of this behavior. It runs as an independent process and does not issue control actions. The only situation when the behavior interacts with other behaviors is a problem with the robot. Then the behavior issues the warning message to all active behaviors and to the Planner. All subsystems of the robot enter the "Emergent Stop" and then "Wait" for an assessment of the situation.

5.2.12 Intelligent Sensing

Raw sensor data provide the robot with the quantitative information about the external world. Then the system, if required can derive the qualitative information about the process. The Intelligent Sensing behavior extracts the information from all sensors of the robot and builds the robot's interpretation of the surrounding world and the internal condition of the robot. The Mission Planner for more flexible coordination of behaviors uses this type of information.

5.2.13 Environmental Sensing

Environmental sensing detects abnormal changes in weather conditions. This behavior does not issue control actions. It carries the informative role in the controls system. But, if the robot detects a high wind, the behavior issues and the system activates the behavior "Reduce Clearance". If this behavior does not help, and the robot tilts, the system activates the behavior “Wait”. Extreme cold or heat will automatically suspend the activity.

5.3 Level of Deliberative Planning

This level of the Deliberative Planner is beyond the scope of the thesis as it involves studying different types of missions and payloads which are not known at the time of design of the control system. In order to provide the functionality of the robot the role of the Mission Planner is restricted to arbitrating behaviors according to their priorities.

5.4 Simulation of behaviors

As a tool for designing behaviors and the Mission Planner for arbitrating of behaviors, the behavior-based control system of the robot was built in MatLab. In addition to simulation of behaviors, it also provides the stimuli on the system simulating the interaction between the robot and the environment. The program implements three basic motions of the robot. These motions are accessible from the user interface shown in Figure 5.2. Each motion can be activated by an individual button.

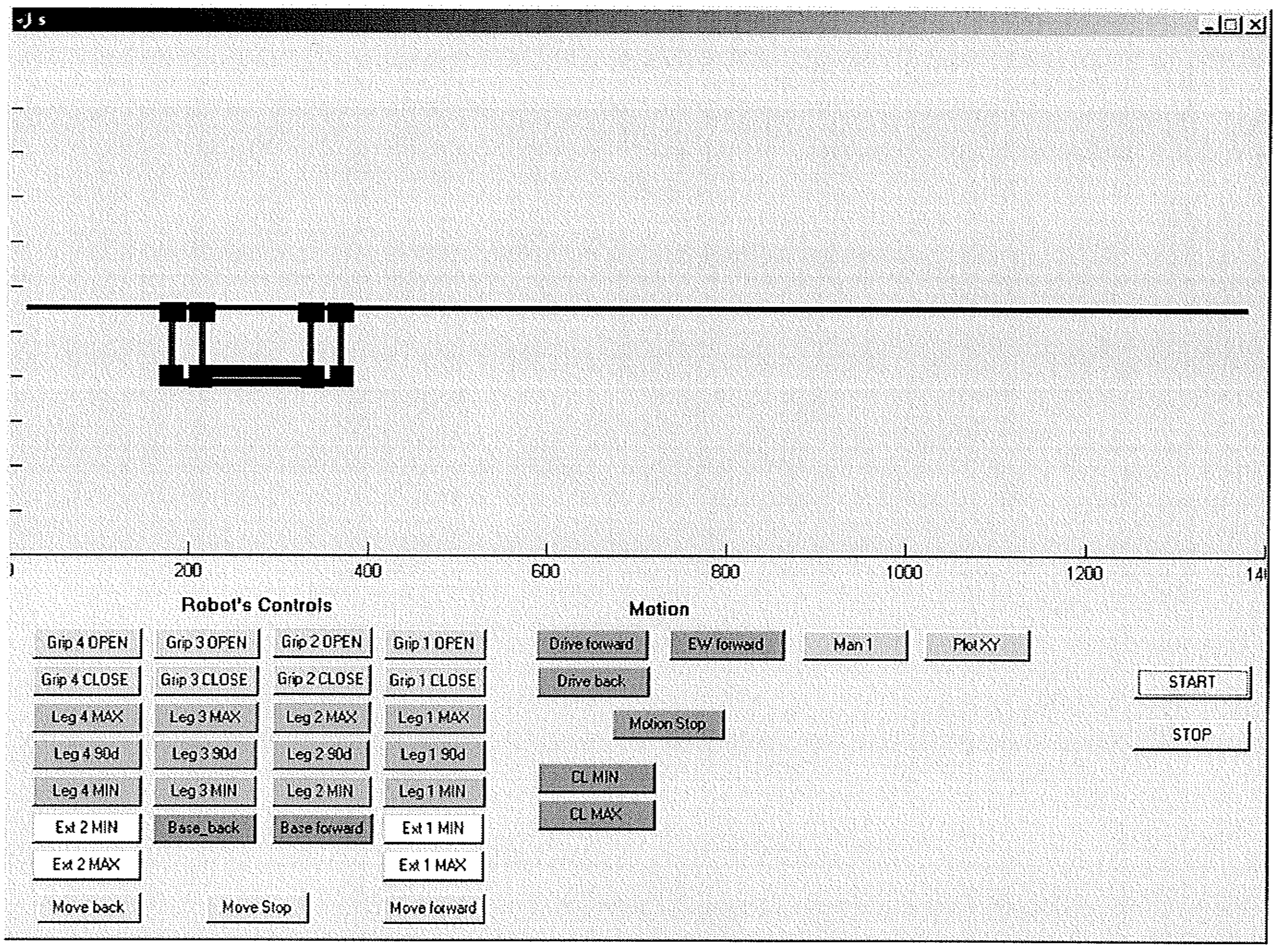


Figure 5.2 Graphical user interface of a simulation program

The robot has a large number of all possible motions and obstacle avoidance maneuvers. Not all of them are presented in the thesis. But, the user can design any required motion in any sequence by getting the access to low-level behaviors. After that, the only thing to do is to describe the selected sequence of low-level behaviors as a high-lever behavior.

The behaviors in the program work in the same way as they would work in a real control system of the robot. This allows considerable reduction of the time for designing the system as all behaviors can be simulated independently and in conjunction with other behaviors prior to implementation of them in a real-world robotic system. Figure 5.2 shows the simulation of the Obstacle Avoidance behavior. The type of obstacle is Large.

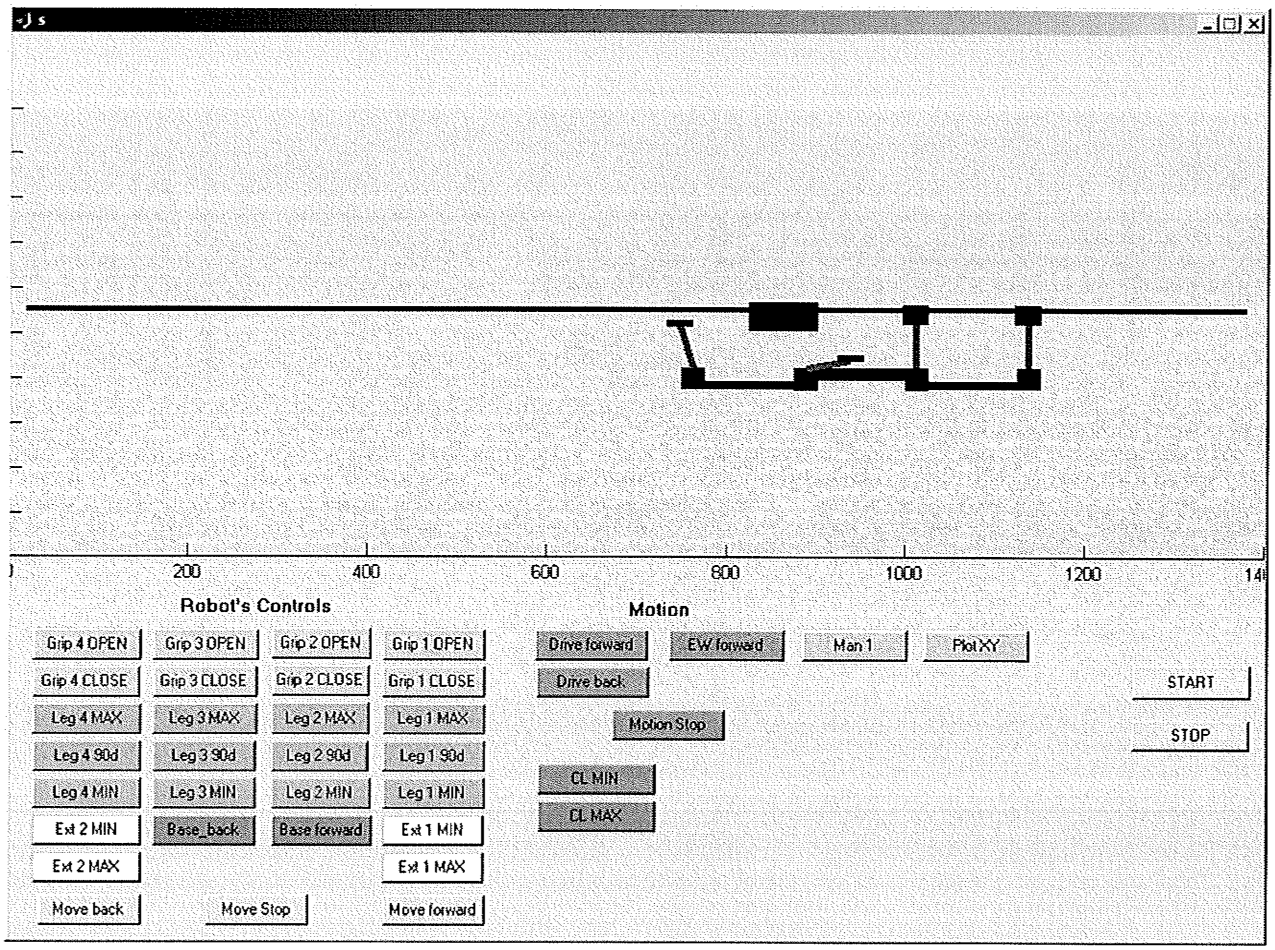


Table 5.2 Fragment of simulation of the obstacle avoidance behavior

Numerical results of the simulation are shown in Figure 5.3. Results represent the positions of robot's parts vs. time. This gives a time framing of behaviors and documents the sequence of low-level behaviors.

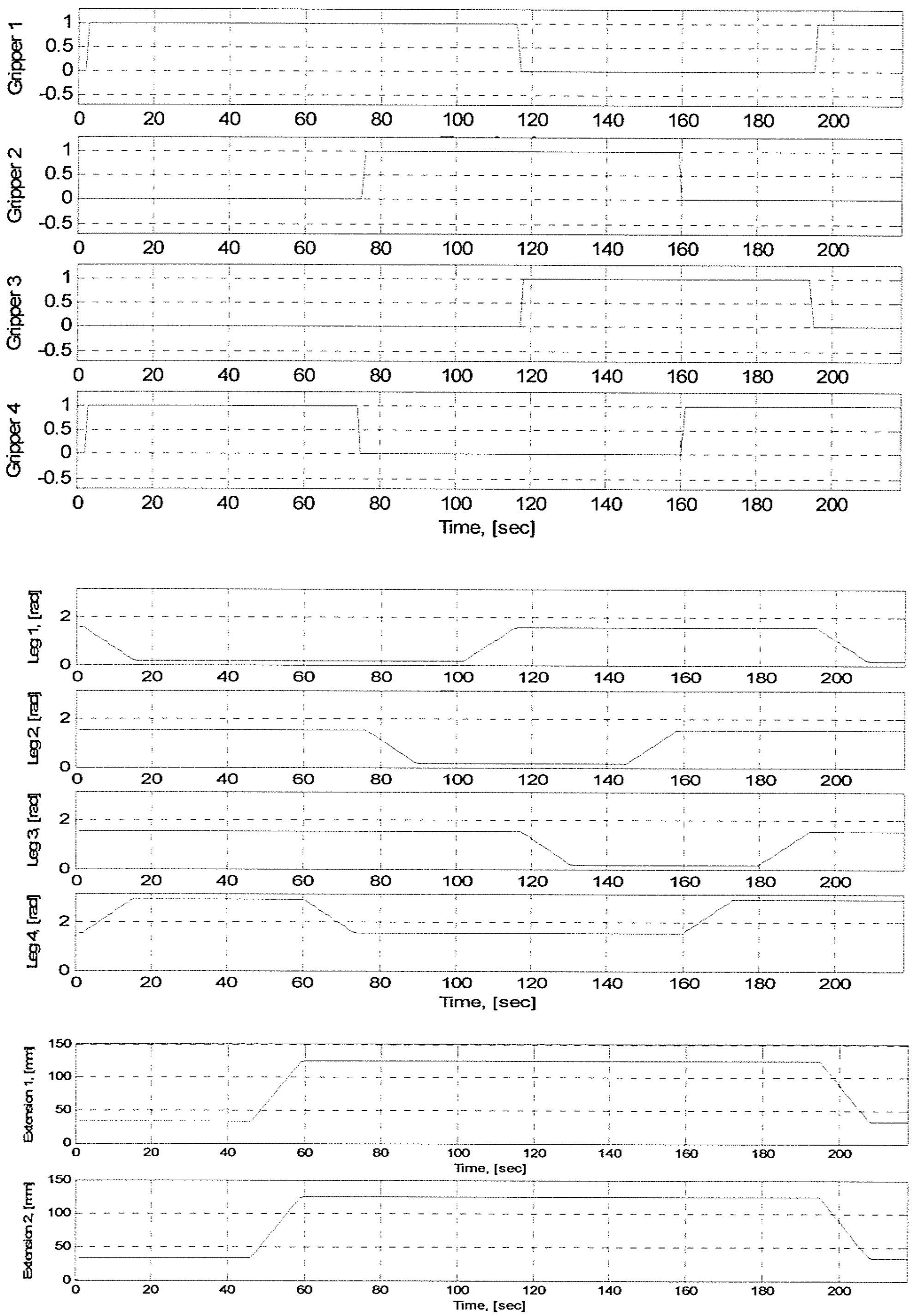


Figure 5.3 Numerical representation of simulation of an obstacle avoidance behavior

6 Conclusion

This thesis presents the design, analysis, and simulation of a robot with an intelligent control system. The design of the robot was done after careful consideration of technical requirements and working conditions of the robot. Designed manoeuvres and motions of the robot exploit the rich potential of the robot which has servo systems adaptable to different configurations of the robot. The servo systems can provide the control of the individual parts of the robot and for a group of parts participating in a cooperative motion. In order to adapt the robot for different missions, the robot has the intelligent behaviour-based control system. The behaviours of the robot reflect different aspects of the robot's life providing the adequate response of the robot on the changing environment, missions and internal states of the robot.

Further research should be done to develop principles of deliberative planning and mission management. Consideration of the other types of obstacles and obstacle avoidance algorithms may increase the area of utilization and performance of the robot.

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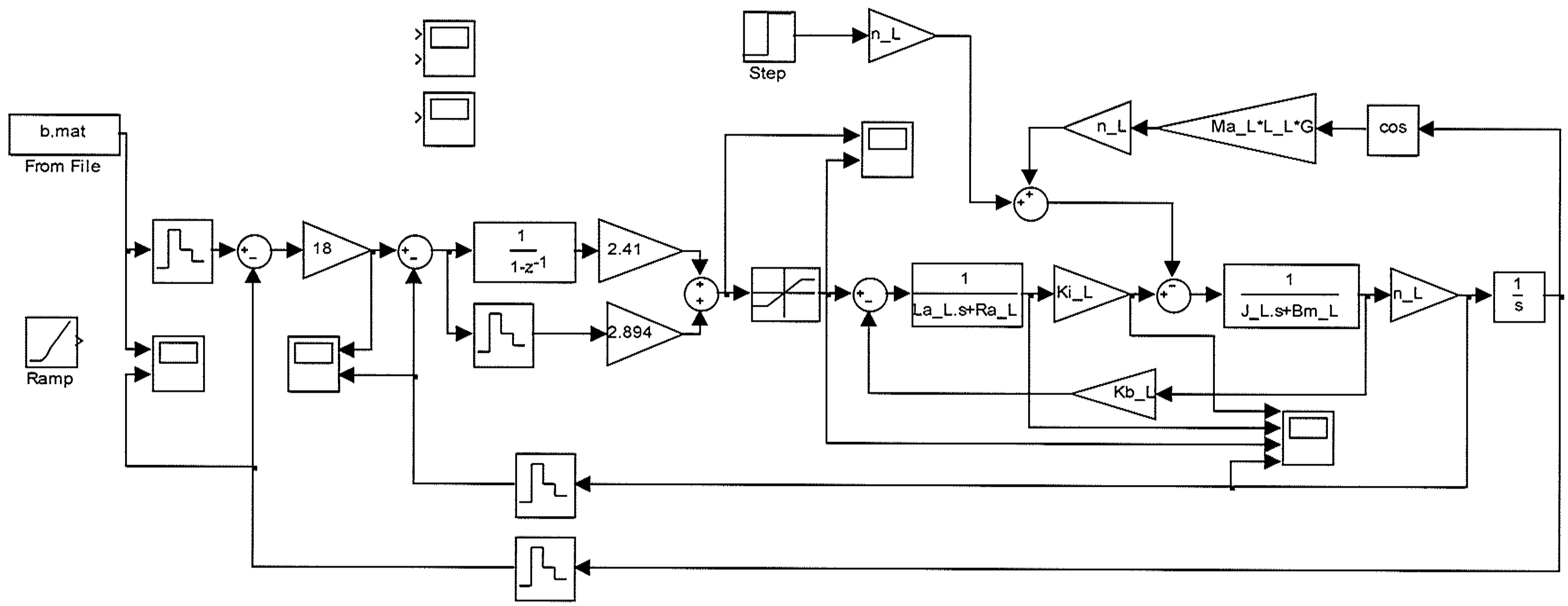
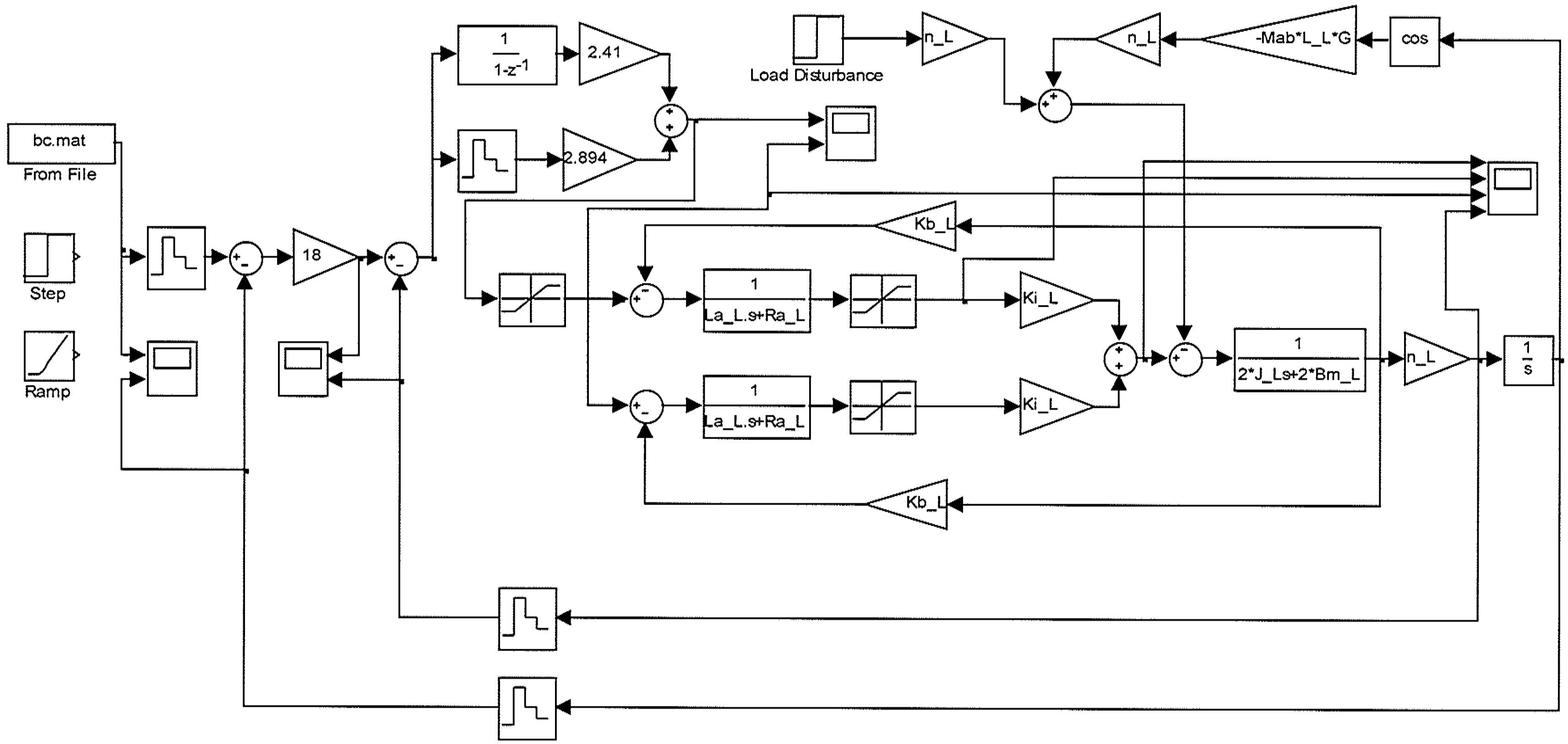
8 Appendix A

Parameters of a DC-motor for a Leg - GM9413-4 (Pittman)

```
%========================================
% Pre-load file for design of leg : leg_design.m
%========================================
clear all;
close all;
% Parameters of DC-motor for Leg - GM9413-4
'Start Initialization of DC-motor GM9413-4 (Leg) '
Ra_L = 2.17;          % [Ohms], Armature-winding resistance
La_L = 1.54e-3;       % [H], Armature inductance
Ki_L  = 19.8e-3;      % [N*m/A], Torque constant
Jm_L = 2.75e-6;       % [kg*m^2], Rotor inertia of the motor
%Bm_L = 1.87e-4;      % [ N*m/(rad/s) ], Viscous friction coefficient
;Bm_L = 7.62e-7;      % [ N*m/(rad/s) ], Viscous friction coefficient
Bm_L = 7.62e-7;
Kb_L = 19.8e-3;       % [ V*s/rad], Back emf constant
n_L = 1/218.4;        % [ - ], gear Train ratio
% Parameters of the Robot
Ma_L = 0.5;     % [kg], Mass of the robot's gripper
Mab = 4;        % [kg], Mass of the robot minus mass of two grippers
L_L = 0.12;     % [m], Length of the Robot's leg
G = 9.81;       % [m/s^2], Free body acceleration
% Computed values
Ja_L = Ma_L*L_L^2;            % [kg*m^2], Moment of inertia of the robots leg
J_L = Jm_L + Ja_L*n_L^2;      % [kg*m^2], Equivalent moment  of inertia
Jab = Mab*L_L^2/2;            % [kg*m^2], Moment of inertia of robot's leg
Ja = Jm_L + Jab*n_L^2;        % [kg*m^2], Equivalent moment  of inertia
```



Appendix A. 1 Servo system for a Single leg mode

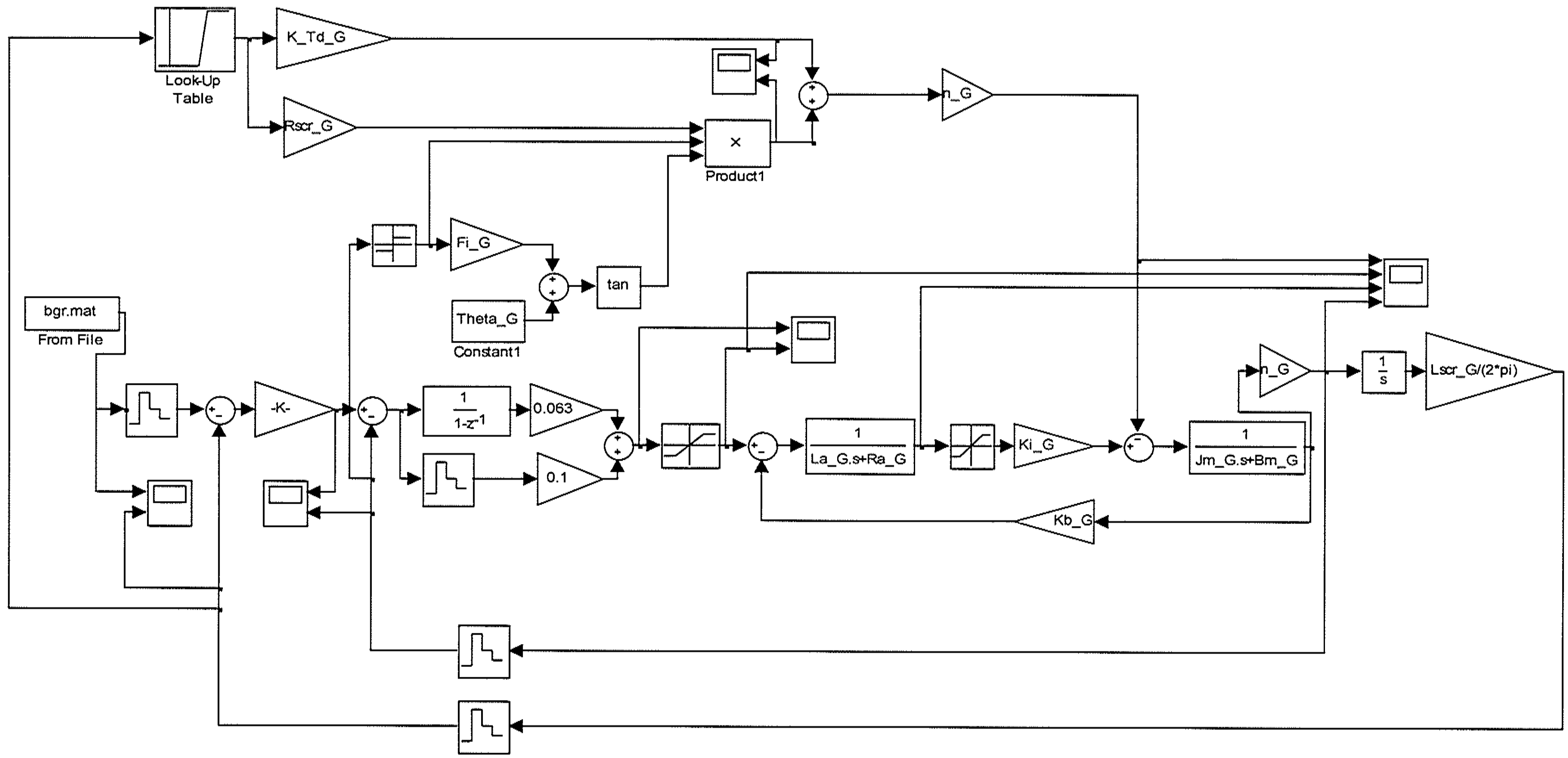


Appendix A. 2 Servo system for a Cooperative mode

Parameters of a DC-motor for a Gripper - GM8712-11 (Pittman)

```
'Start Initialization of DC-motor GM8712-11 (Gripper) '
' 12-Volt Winding'
Ra_G = 4.38;          % [Ohms], Armature-winding resistance
La_G = 2.15e-3;       % [H], Armature inductance
Ki_G  = 13.7e-3;      % [N*m/A], Torque constant
Kb_G = 13.7e-3;       % [ V*s/rad], Back emf constant
Jm_G = 9.18e-7;       % [kg*m^2], Rotor inertia of the motor
Bm_G = 5.87e-7;       % [ N*m/(rad/s) ], Viscous friction coefficient
n_G = 1/6.3;          % [ - ], gear Train ratio
Mdc_G=0.1936;         %[kg], motor- 0.127, gear - 0.0666
% Parameters of the Robot
Lscr_g=1/32;          %[inch], Screw lead
Rscr_g=3/32;          %[inch], Radius of thread -> convert to meters
g = 9.81;             %[m/s^2], Free body acceleration
Mr=4;                 %[kg], Mass of the Robot
%Mu_b=0.25;           %[ - ], coefficient of kinetic friction (), case b, catch the wire
Mu_G=0.20;            %[ - ], coefficient of kinetic friction (steel-bronze)
Lmin_G=0;             %[m], minimum length of the lead screw
Lmax_G=0.04;          %[m], maximum length of the lead screw
M_load=0.05;          %[kg], mass of the load
% Computed Values
Lscr_G=inch2m(Lscr_g);              %[m], Conversion from inch to meters
Rscr_G=inch2m(Rscr_g);
Rg=2*Rscr_G;                        %[m], radius of collar bearing
Wmax=Mr*g*(1+1/2)/2;                %[N], Maximum weight
Wmin=0.01*Wmax;                     %[N], Minimum weight
Fi_G=atan(Mu_G);                    %[rad], Angle of kinetic friction
Theta_G=atan(Lscr_G/(2*pi*Rscr_G));      %[rad], Angle of the lead screw
Ja_G = M_load*(1/2)*(Lscr_G/(2*pi))^2;   % [kg*m^2], Moment of inertia of the
robots leg
```

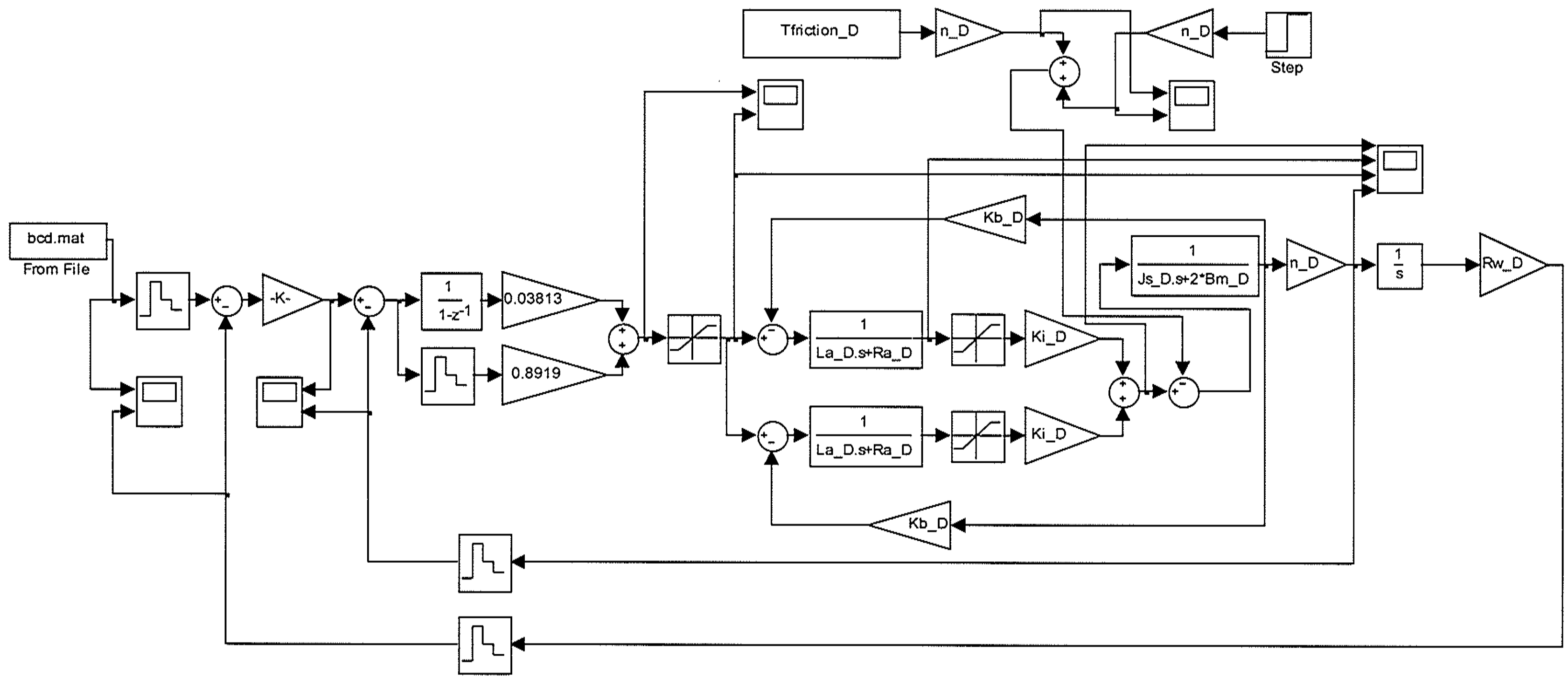
```
J_G = Jm_G + Ja_G*n_G^2;                 % [kg*m^2], Equivalent moment of inertia
K_Td_G=2/3*Mu_G*(Rg^3-Rscr_G^3)/(Rg^2-Rscr_G^2); %Part of Disc friction torque
```



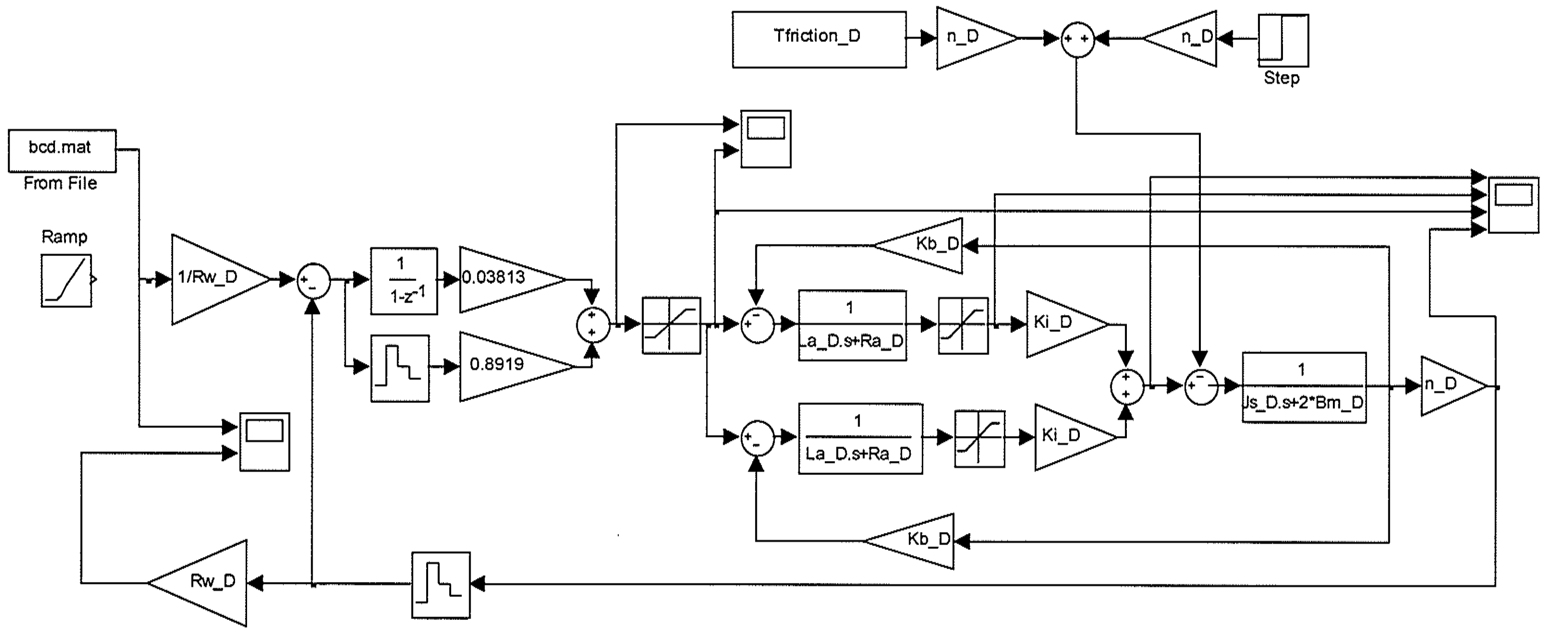
Appendix A. 3 Servo system of a gripper

Parameters of DC-motor for Driver - GM8712-11 (Pittman)

```
'Start Initialization of DC-motor GM8712-11 (Drive) '
' 12-Volt Winding'
Ra_D = 4.38;          % [Ohms], Armature-winding resistance
La_D = 2.15e-3;       % [H], Armature inductance
Ki_D  = 13.7e-3;      % [N*m/A], Torque constant
Kb_D = 13.7e-3;       % [ V*s/rad], Back emf constant
Jm_D = 9.18e-7;       % [kg*m^2], Rotor inertia of the motor
Bm_D = 5.87e-7;       % [ N*m/(rad/s) ], Viscous friction coefficient
n_D = 1/6.3;          % [ - ], gear Train ratio
Mdc_D=0.1936 ;        % [kg], motor- 0.127, gear - 0.0666
% Parameters of the Robot
Rw_D = 0.01;          % [m], Radius of driving wheel
Ro_d=3/32;
g = 9.81;             %[m/s^2], Free body acceleration
Mr=5;                 %[kg], Mass of the Robot
Mu_D=0.20;            %[ - ], coefficient of kinetic friction (steel-polyvinyl)
% Computed Values
Wmax=Mr*g/2;                        %[N], Maximum weight
Wmin=0.01*Wmax;                     %[N], Minimum weight
Ro_D=inch2m(Ro_d);                  % [m], Radius of the wheels' rod
Fi_D=atan(Mu_D);                    %[rad], Angle of kinetic friction
Ja_D = (Mr/2+Mr/4)*Rw_D^2;          % [kg*m^2], Moment of inertia of the robot
J_D = Jm_D + Ja_D*n_D^2;            % [kg*m^2], Equivalent moment of inertia
Tfriction_D=(Mr+Mr/2)*g*Ro_D*sin(atan(Mu_D));
Js_D=2*Jm_D+2*Ja_D*n_D^2;
```



Appendix A. 4 Servo system of drive unit for a distance control



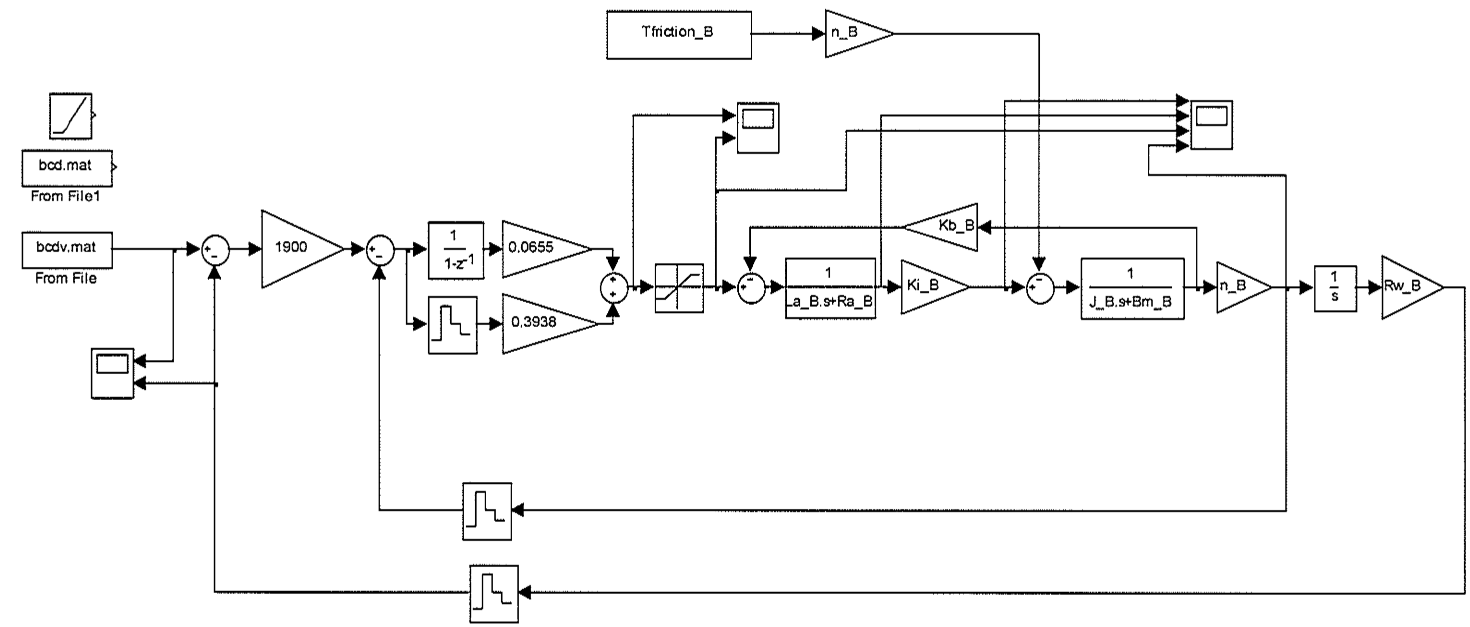
Appendix A. 5 Servo system of drive unit for a speed control

Parameters of DC-motor for the Base - GM8712-11 (Pittman)

```
'Start Initialization of DC-motor GM8712-11 (Base) '
' 12-Volt Winding'
Ra_B = 4.38;        % [Ohms], Armature-winding resistance
La_B = 2.15e-3;     % [H], Armature inductance
Ki_B  = 13.7e-3;     % [N*m/A], Torque constant
Kb_B = 13.7e-3;     % [ V*s/rad], Back emf constant
Jm_B = 9.18e-7;     % [kg*m^2], Rotor inertia of the motor
Bm_B = 5.87e-7;     % [ N*m/(rad/s) ], Viscous friction coefficient
n_B = 1/6.3;         % [ - ], gear Train ratio
Mdc_B=0.1936 ;      % [kg], motor- 0.127, gear - 0.0666

% Parameters of the Robot
Rw_B = 0.01;        % [m], Radius of driving wheel
Ro_b=3/32;          % [inch], Radius of the wheels' axes
g = 9.81;            %[m/s^2], Free body acceleration
Mr=3;                 %[kg], Mass of the Robot
Mu_B=0.20;          %[ - ], coefficient. of kinetic friction (steel-polyvinyl)


% Computed Values
Ro_B=inch2m(Ro_b);                  % [m], Radius of the wheels' rod
Ja_B = Mr*(1/2)*Rw_B^2;              % [kg*m^2], Moment of inertia of the robot
J_B = Jm_B + Ja_B*n_B^2;                 % [kg*m^2], Equivalent moment of inertia
Tfriction_B=Mr*g*Ro_B*sin(atan(Mu_B));
Js_B=2*Jm_B+2*Ja_B*n_B^2;
```



Appendix A. 6 Servo system for a single base extension