B.Tech. Seminar Report

Robot Leg Mechanisms

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Contents

Abstract

This paper describes designs of the leg drive mechanisms, hardware architecture and the leg control methods for walking machines. The body of knowledge that applies to mobile wheeled robots is quite well developed. However, autonomous walking vehicles are still relatively new, and the body of knowledge concerning their development is not as well defined. The difficulty factor in building a legged robot is also considerably higher than that for a wheeled robot.

In this report a brief introduction is given in beginning on limitations of wheeled and tracked wheeled robots in rocky and hilly terrains and stepped and discontinues paths. The human leg and walking gait, control system, the musculo-skeletal system and the central nervous system have been discussed.

Brief guidelines for the design of leg mechanisms have been presented through the study of various joints, links, sensors and degrees of freedoms in legs. Then a study of various robot leg mechanisms is made to identify their applications and advantages.

At the end this paper describes mechanism and control of leg-wheel hybrid mobile robot. Legged locomotion has high adaptability for rough terrain, and wheeled locomotion posses speed and efficiency. A new locomotion mechanism that combines legs and wheels is proposed.

Chapter 1

Introduction

Traditionally, most mobile robots have been equipped with wheels. The wheel is easy to control and direct. It provides a stable base on which a robot can maneuver and is easy to build. One of the major drawbacks of the wheel, however, is the limitation it imposes on the terrain that can be successfully navigated. A wheel requires a relatively flat surface on which to operate. Rocky or hilly terrain, which might be found in many applications as forestry, waste clean-up and planetary exploration, imposes high demands on a robot and precludes the use of wheels. A second approach to this problem would be to use tracked wheel robots. For many applications this is acceptable, especially in very controlled environments. However, in other instances the environment cannot be controlled or predicted and a robot must be able to adapt to its surroundings. Such a surrounding can be places where robots would have to step over the obstacles such as a surface where pipes are running and where they have to move on discontinuous terrain like steps. Research into legged robotics promises to overcome these difficulties.

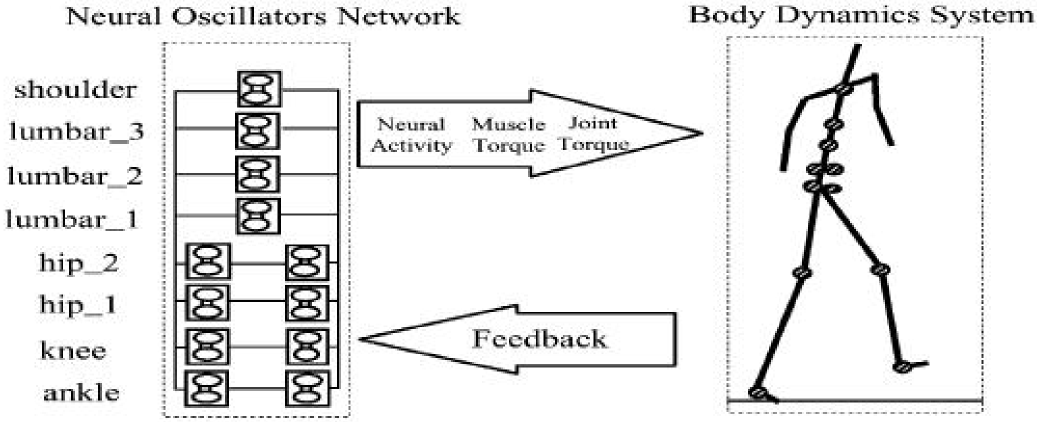
The complexity of control required for a legged robot to navigate autonomously over unfamiliar terrain has made them difficult to build. Recent developments in embedded controller technology have yielded very sophisticated computing devices in relatively small, easily programmed modules. With these advanced components, it is now possible to control relatively complex and sophisticated devices.

Chapter 2

Human Walk

Human walk is the most efficient bipedal walk known. It uses a dynamic walking gait. At any given condition, i.e. at any walking speed and step rate, a human chooses the most energy efficient gait for locomotion. In steady state, walking is symmetric and periodic.

The physical structure of a human body consists of the musculo-skeletal system for the physical realization of the walking gait and the central nervous system for the optimization and control of the gait. The skeletal system consists of the bones which are actuated by the muscles on the skeletal system. The sole and knees are designed to minimize the ground impact forces by use of soft tissue at the sole and also by bending of the knees.



The neuronal system autonomously produces rhythmic patterns of neural stimuli and the system of body dynamics generates movements according to the rhythm pattern. Information concerning somatic senses, such as information about foot– ground contacts and segment angles, is fed back to the neuronal system, and the rhythm pattern of neural stimuli is regenerated based on this information. This theory holds that this interaction between the neuronal system and the system of body dynamics produces movement.

The theory holds that the rhythmic pattern is generated by a network of interneurons in the spinal cord called the Central Pattern Generators (CPGs). These consist of pair of neurons called the neural oscillators. A neural oscillator consists of a pair of flexor and extensor neurons and each neuron produces a signal for either flexion or extension motion of a joint. A neural oscillator exists for each degree of freedom of the joint. The neural oscillators are able to generate the basic rhythm of joint movements in walking due to their mutual inhibition. Human locomotion is thought to use a number of principles which simplify control.

The sensory feedback to the central nervous system is given by sensory receptors of joint angles and angular velocities. The somatic sensors give pressure distribution on the sole and the inclination angle and its orientation information. The eyes also help in the coordination movement and in the identification of obstacles.

Chapter 3

Study of Robot Leg Mechanisms

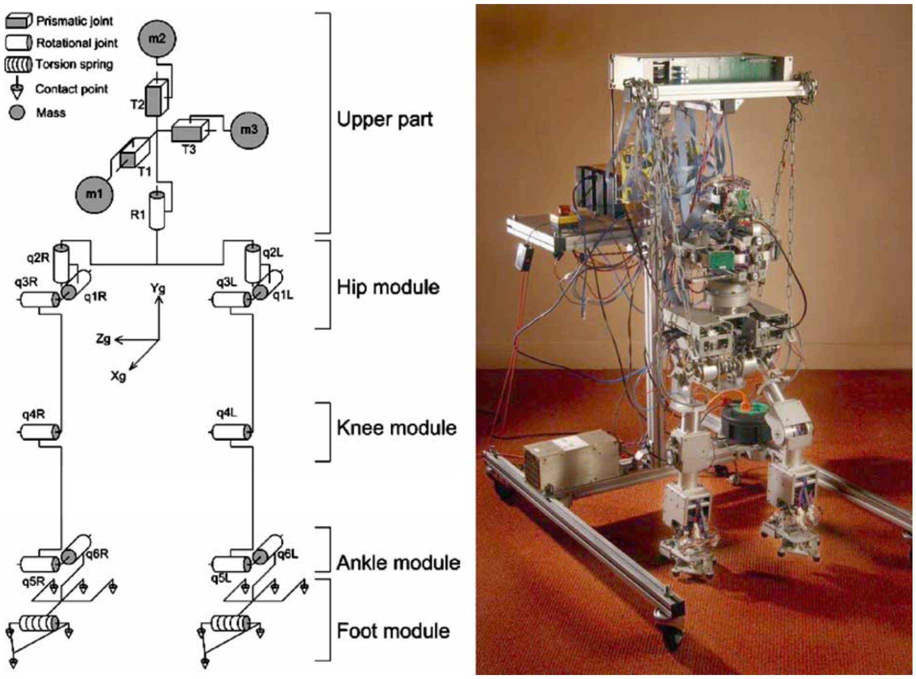
In comparison with the industrial manipulators, the task of building an adaptable, autonomous walking machine is more difficult. Walking machines have more active degrees of freedom (DOF) than industrial robots. To enlarge the work-space of the leg-end, and thus enhance the machine's ability to adapt to the terrain, each leg should have at least 3 DOF, which results in a total of 12 DOF for a quadruped or 18 DOF for a hexapod. All those joints must be controlled adequately in real time. This also means that the hardware and software systems must meet more critical requirements than those formulated for industrial robot controllers. Moreover, fully autonomous vehicles use only on-board controllers and so those controllers have to be miniaturized to an utmost extent. Mechanical structure of a walking machine should not only imitate the leg structure of living creatures (e.g., insects, spiders), but should also take into account the actuating systems properties (e.g., size, weight and power of the motors) and constraints (e.g., size of the body and the leg work-space).

The need for a general solution to the problem of robot legs design that can be used either by two-, four- or six-legged vehicles, is clear. However the ability to meet this need has been hampered by the lack of adequate joint mechanisms and controls. Joint technology is a key problem in the development of such vehicles, because hip and ankle joints require, at a minimum, pitch and yaw motion about a common center with remote location of actuation sources analogous to our muscles and joints. The lack of simple, compact, cost-effective and reliable actuator packages has also been a major stumbling block in current designs. Ineffective joint design leads to unwieldy vehicles that compensate for the instability of their simple joints by means of additional legs.

Following subjects are found important to study the leg mechanism.

1). Effectiveness of leg joints relating to the walking.
2). Locations of leg joints.
3). Movable extent of leg joints.

4). Dimension, weight and center of gravity of a leg.
5). Torque placed on leg joints during the walking.
6). Sensors relating to the walking.
7). Grounding impact on leg joints during the walking.



3.1 Effectiveness of leg joints relating to the walking.

It is found that the walking was not affected even if there were no fingers and that the roots of the fingers and heel are more important for supporting the body weight. As far as the ankle joint and walking function are concerned, if the ankle joints were fixed

- there will be a lack of contact feeling with ground surface and the fore-and-aft
- standing still is difficult if eyes were closed and
- when side crossing a sloped surface, the feeling of contact with ground surface stability will be weak.

As far as the knee joint, it is found that if the knee joints were fixed, walking up and down staircase is not possible.

3.2 Locations of leg joints.

The location of leg joints affects the kinematic and dynamic properties of leg. These have been explained in detail in later part.

3.3 Movable extent of leg joints.

Again the length of the leg links and location of leg joints affect the movement and reach of the legs which determines the gait of walking on flat surface and up and downs of staircase.

3.4 Dimension, weight and center of gravity of a leg.

Placing the actuator at the knee joint adds various dynamic effects to the leg which have to be compensated for by the controller. This adds complexity to the control algorithms needed to move the leg. It also requires more powerful motors at the hip joint to move the added mass of the leg. Remote actuation, in which the actuators are located at the base of the leg, eliminates some of these problems, at the cost of increasing the complexity of the mechanism.

3.5 Torque placed on leg joints during the walking.

This is one of the most important aspects. The whole moment of leg depends upon the torque requirement on leg joints. If the actuators are not powerful enough to provide the required torque the expected gait cannot be achieved.

3.6 Sensors relating to the walking.

Humans have three senses for sensing the equilibrium. One is the sensor to sense acceleration by ear drum; the second one is the sensor to sense the tipping rate by semicircular canals and the third one is the sensor to sense the angles of joints movement, angle acceleration, muscular strength, pressure feeling of foot sole and skin. We also have the visual sensor which complements and alternates the sense of equilibrium mentioned above and also manages the walking information. Basing on this information, it can be concluded that a robot in its system needs a G-sensor, 6 axis force sensor and gyro meter to sense its own posture and joint angle sensor in order to grasp the leg movement when walking.

3.7 Grounding impact on leg joints during the walking.

The ground reaction force is the impact force imposed on the foot during the walking. Human body is so designed to absorb the impact force with its soft skin tissues surrounding the foot, arch frame of bones forming the foot, and the roots of finger joints, and flexible movement of knee joint as the foot land the ground. As the walking speed increases, the reaction force becomes larger even with the human’s impact damper mechanism.

3.8 The requirements for an ideal walking machine:

1. The machine must have a uniform velocity while the feet are in contact with the ground.
2. The stride must be long in relation to the physical dimensions of the walking machine to achieve adequate speeds.
3. The height and length of the stride must be controllable by the operator.
4. The height of the step should be large compared with the dimensions of the machine.
5. The 'feet' should have a high stride to return-time ratio.
6. A mechanism integral to the 'legs' must be provided for steering the body.
7. The body must be capable of moving either in the forward or reverse directions.
8. The inertia forces and torques must be balanced.
9. The energy lost in lifting the foot should be recovered in lowering the foot.
10. The height of the 'body' of the machine above the ground should be controllable by the operator.

Chapter 4

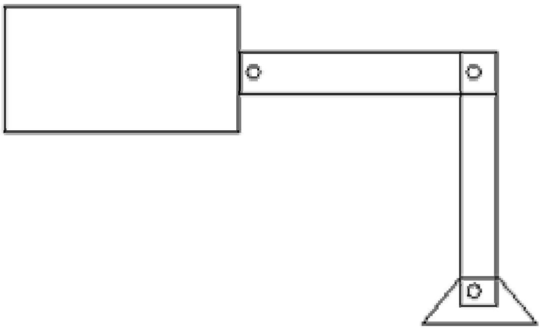
Leg Mechanisms

If one stops to consider for a moment it becomes immediately evident that the earth is literally crawling with walking machines. The locomotion of all organisms in nature is produced by a system of levers. In some cases, such as the caterpillar, the whole animal can be considered a single lever but, nevertheless, the motion can be reduced to a levered system. The fact that nature has confined herself to levered machines should be extremely significant to the designer of off-road equipment.

The successful design of a legged robot depends to a large extent on the leg design chosen. Since all aspects of walking are ultimately governed by the physical limitations of the leg, it is important to select a leg that will allow for a maximum range of motion and that will not impose unnecessary constraints on the walking gait chosen. The first stage of the leg design process therefore consists of a search for an optimal leg design.

4.1 Simple two-link leg

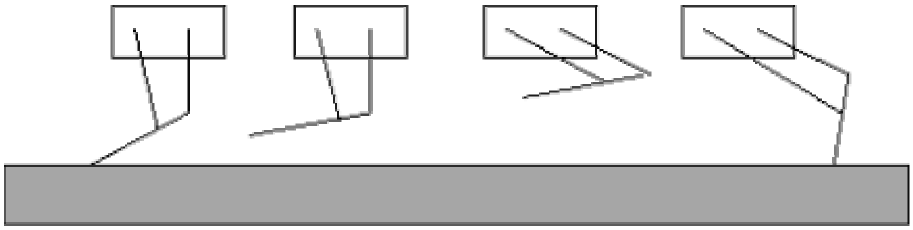
This design consists of two links connected through a knee joint. The walking motion is accomplished by controlling the angle of the two links to position the end effecter, or foot. The entire leg is mounted on a swiveling base in order to advance and retract the leg. There are a number of different ways in which the joints can be actuated, with the actuation of the knee joint being the major difference from one design to the next. Options include mounting the motor at the joint itself or using a pulley, chain or lead screw to set the angle of the knee using an actuator mounted near the base of the leg.



The major drawback of this design is the necessity to actuate remote joints. Placing the actuator at the knee joint adds various dynamic effects to the leg which have to be compensated for by the controller. This adds complexity to the control algorithms needed to move the leg. It also requires more powerful motors at the hip joint to move the added mass of the leg. Remote actuation, in which the actuators are located at the base of the leg, eliminates some of these problems, at the cost of increasing the complexity of the mechanism. The coupling of the motion of the end effecter relative to the actuators is another undesirable characteristic of this leg design.

4.2 Mammalian Leg

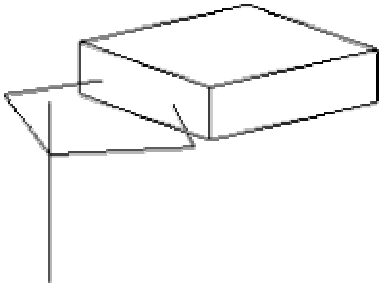
Another potential leg design considered is modeled after a typical mammalian leg. The basic walking motion is shown in figure below. The entire leg swings about the hip joint to advance and retract the leg while the angle of the knee joint is controlled to lift the foot out of the way during the advance phase. The leg can be designed using a four bar linkage structure with one of the links being of variable length.



The motions are highly coupled and the effective workspace is somewhat limited. Also, the fact that the entire weight of the robot is supported by the hip joint necessitates a large, powerful and potentially expensive motor, which does not conform to the design criteria set out for a good leg design.

4.3 Pentagraph Leg

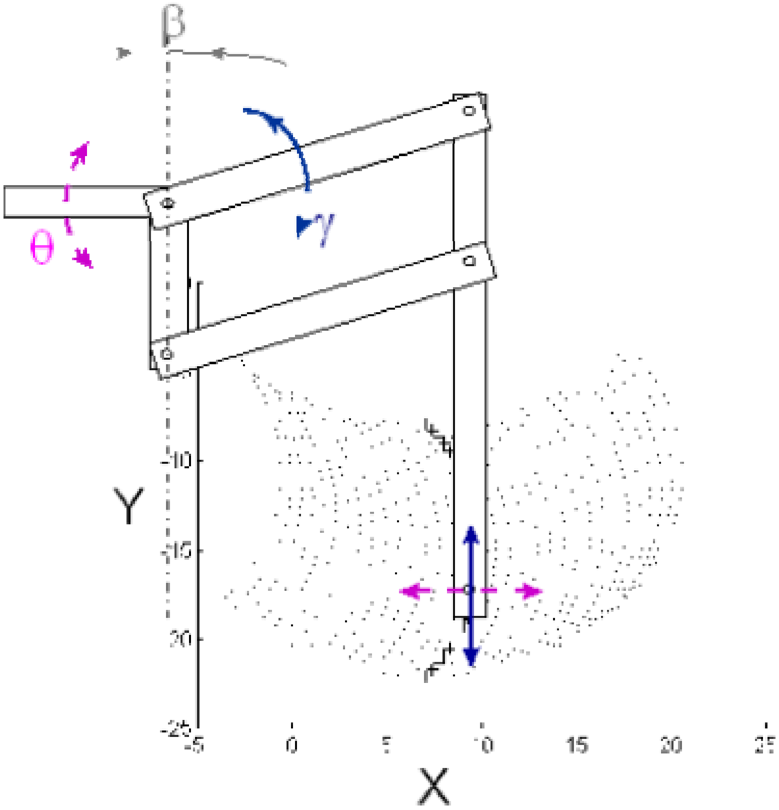
A pentagraph, or five-bar mechanism, has been used in other robotic applications to provide mechanical transparency of a linkage structure. By situating the actuators at a central base and using light members, the dynamic effects of the mechanism can be minimized while still providing structural rigidity. An adaptation of this technology to legged robots is shown in figure below. The planar five-bar mechanism could be used to position the leg shaft in a plane. The shaft or the entire leg platform could then be controlled to provide motion in the third axis.



One of the major drawbacks of this arrangement is the high degree of coupling of the motion. It is not possible to move the position of the end effecter in a particular direction without moving at least two motors simultaneously. This complicates the control algorithm necessary to move the leg.

4.4 Pantograph Leg

The pantograph leg design has proven popular for a number of different legged robots appearing in the literature. The pantograph mechanism consists of a simple four bar parallelogram mechanism. This simplifies the kinematics associated with the mechanism and thereby reduces the computational complexity of the control (see figure below).

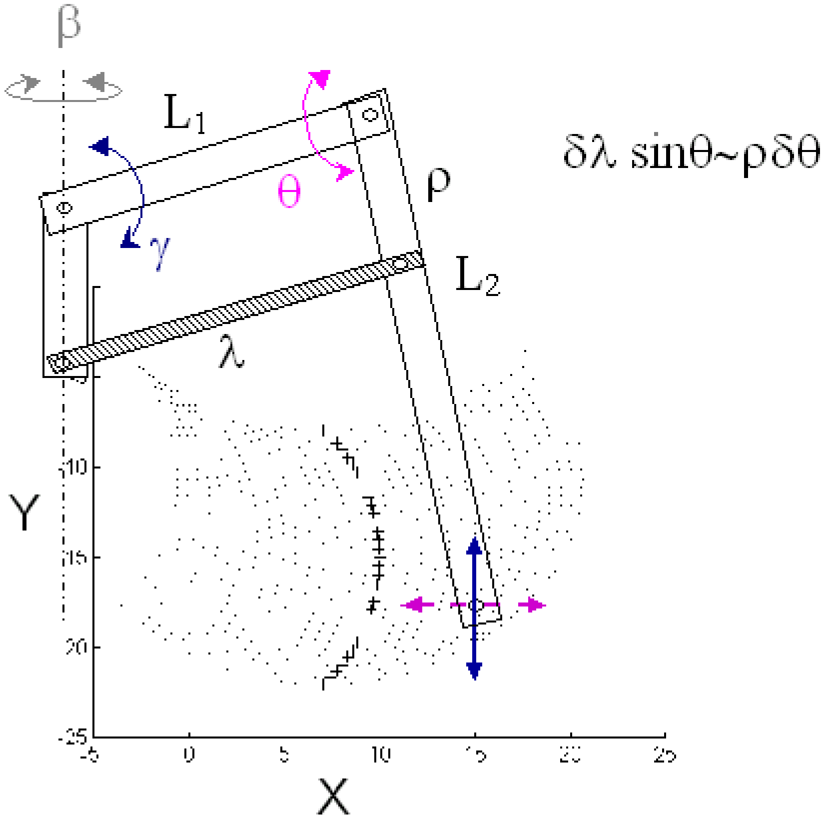


The workspace of the leg shows that with this configuration there is still some coupling of the end effecter motion, which results in the curved trajectories of the foot evident in the figure. It simplifies geometry.

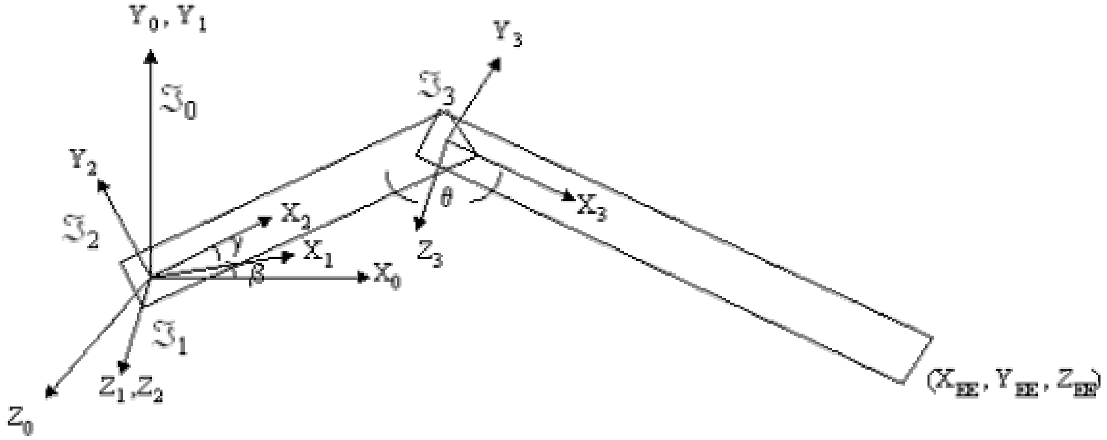
Chapter 5

Study of Simple Two-Link Manipulator Leg Design

Actuation of the remote joint is accomplished using a lead screw and the new leg configuration is shown in figure below. The measured quantity at the knee joint is the angle ‘θ ’ while the controlled element is the length ‘λ ’. For small changes, the relationship between these two quantities, as shown in the figure, holds true. Since the controller will be updating its control signal at a high rate, this approximation is sufficient.



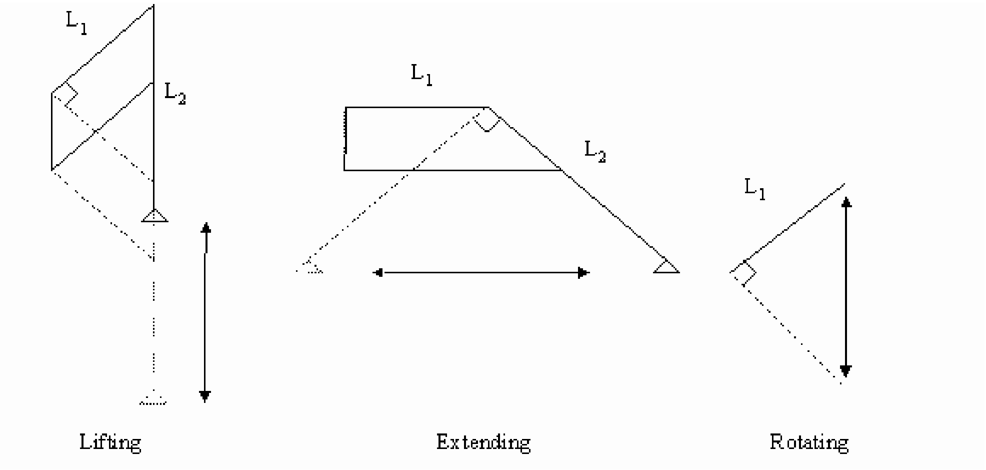
Accurate calculation of the foot position will be necessary when precise foot placement is critical, such as when the robot is navigating in rough or otherwise uncertain terrain. If the robot is given the ability to select its foot placements it must be able to move the leg to the appropriate configuration. The position of the end effecter in space (in this case the foot of the robot) can easily be calculated if the angles γ , θ and β are measured as shown in figure below.



The position of the foot in space is given by following equations:

$$X_{ee} = \left(L_1 \cos\gamma + L_2 \left(\sin\gamma \sin\theta - \cos\gamma \cos\theta \right) \right) \cos\beta$$
$$Y_{ee} = L_1 \sin\gamma - L_2 \left(\sin\gamma \cos\theta - \cos\gamma \sin\theta \right)$$
$$Z_{ee} = -\left(L_1 \cos\gamma + L_2 \left(\sin\gamma \sin\theta - \cos\gamma \cos\theta \right) \right) \sin\beta$$

A critical consideration during the design stage is the size of the desired workspace of the leg, and hence the size of the leg. The lengths of the various links determine the height to which the leg can be lifted, the distance that the leg can be extended away from the body and the size of each step. There are no fixed constraints on the size of the robot, other than the fact that a larger robot will tend to incur higher costs.



Chapter 6

Control system

6.1 Functional decomposition

- The lowest level includes joint control. The angular joint positions are evaluated from the leg-end trajectory shape defined in Cartesian space. Inverse kinematics model is implemented there to evaluate the joint angular positions. Incremental rotary optical encoders mounted on motor shafts are used as the feedback devices. The motor controllers use the PID algorithm to compute the angular positions
- The upper level – leg level produces the leg-end trajectory according to the proper timing scheme.
- The next level is the gait level. The rhythmic and free gait will be generated by it. In the case of pick and place operations, this level will also generate trajectories of front legs treated as manipulators.
- The uppermost level of the control software will be responsible for the generation of the body (body level) trajectories according to the user commands or according to the sensory readings. For the gait and body level, the most serious problem is to elaborate the method of free gait generation taking into account that there are obstacles of different size and density which must be avoided.

The transition from one state to another is performed taking into account: stability conditions, sensory readings, goal of machine motion and leg-end coordinates of other legs. Free gait must be statically stable, i.e., projection of vehicle center of gravity must be inside the support polygon. The planning of free gait is executed in parallel for all the legs. Force-control feedback is included in the leg level of the controller functional structure. Force control is made along the directions in which the leg-end is constrained by the environment (direction normal to the ground level) and pure position control is executed along the other directions, in which the leg is unconstrained and so free to move.

6.2 Structure of the hardware system

The hardware structure of control system includes: Controller (leg CPU), motion control cards (PID controllers) connected to the amplifiers powering the leg motors. To provide position feedback digital encoders are used. Leg-end has piezoelectric force sensor coupled through an amplifier to an A/D converter that delivers the data to the controller. Sampling rate (time necessary to obtain the encoder readings, compute the set values and attain them) depends on the motor control method (PWM or voltage control) to a minor extent.

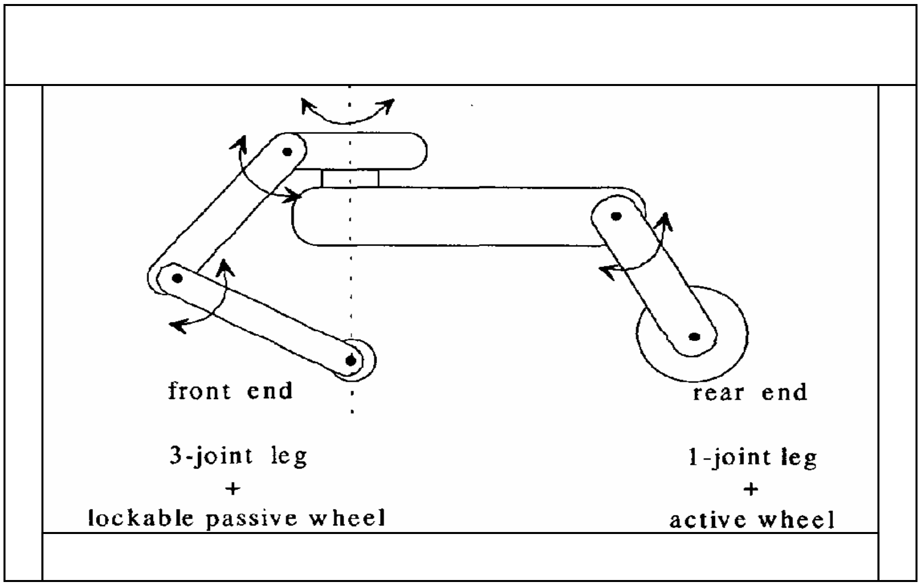
Chapter 7

Mechanism of a Leg-Wheel Hybrid Mobile Robot

Legged locomotion has high adaptability for rough terrain, and wheeled locomotion posses speed and efficiency. A new locomotion mechanism that combines legs and wheels is proposed.

In the case of outdoor works, mechanization such as construction machines has been done only on relatively flat terrain. Most of works in the mountain sites depends on human labors. For the future, the works in such area will become important from the point of view of the prevention of natural calamities or the environmental problems. To automate such works, development of the locomotion system that can move in mountainous environment is essential. The mountain environment includes steps, inclined terrain, and easily deformed and collapsed terrain. Many mobile robots for outdoor environment are equipped with wheels or crawlers. However, they cannot move on discontinuous terrain like steps. Although legged robots have great adaptability for complicated environment, they have some difficulties also. Generally, legged robots require large number of actuators and complicated mechanism. Moreover, their walking speed is slow even on flat terrain.

Let us discuss here a prototype mobile robot that adopts the mechanism. The robot has four legs, and a wheel is attached at the end of each leg. The front leg has three joints and a passive wheel. The rear leg has one joint and an active wheel. In order to make the best of the mechanism, three locomotion modes, wheel mode, hybrid mode, and step mode, are developed. In the wheel mode, four wheels are used on flat terrain. On the rough terrain, the hybrid mode is select, and two legs and two active wheels are used for locomotion. To climb or descend a large step, the step mode is used.



7.1 Locomotion mechanism and environment

Consider the classification of the environment from the contact between locomotion mechanism and the ground.

- When terrain is flat, the locomotion mechanism can always keep contact with the ground. We call this kind of terrain continuous contact locomotion environment. In this environment, conventional wheels and crawlers are available. Although wheels and crawlers have different locomotive capability, both mechanisms always keep contact with the ground during locomotion. The trace of movement in this environment is continuous lines.
- One of the causes wheeled or tracked vehicle cannot move is existence of obstacles like steps. We call the terrain that includes such obstacles discontinuous contact locomotion environment. In order to move in this kind of environment, robots that have actively suspended wheels or shape-changeable crawlers have been developed. In this environment, a mechanism that switches the contact point between the locomotion mechanism and the ground is essential. The trace of the movement is line segments.
- More serious environment is discrete contact locomotion environment. In this environment, continuous contact between locomotion mechanism and the ground

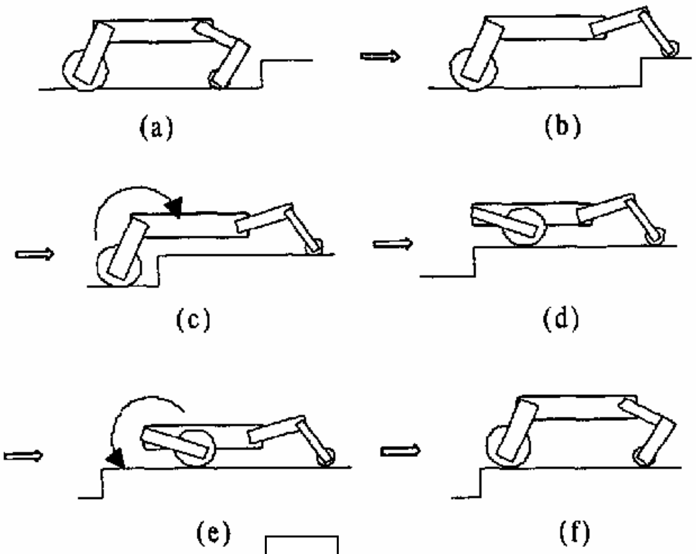
is not allowed. Locomotion mechanism has to support and propel the robot only by using discrete point contacts with the ground. Robots in this environment must be equipped with legs. The trace is sequence of points.

7.2 Proposed locomotion mechanism

Requirements of mobile robot

1) On flat terrain, fast and efficient locomotion is realized with simple control.
2) The robot can move in the discontinuous contact locomotion environment.
3) For, the movement on steep slope, traction is generated at the all contact points between the robot and terrain.
4) In order to increase the reliability and decrease the cost, the robot has less number of actuators than normal legged robot.

Many mobile robots developed earlier have an active wheel at the tip of their leg. Though such a mechanism shows high adaptability to the environment, it requires large number of actuators. In this scheme, different kinds of mechanism are employed at the front end and rear end in order to decrease the number of actuators. The robot has two front legs and two rear legs. Front leg has a serial link structure, and has three rotational joints. A relatively small lockable passive wheel is attached at the tip of each front leg. The first joint, that links the body and the thigh, has vertical axis and the second and third joints have horizontal axis. End of the front leg (passive wheel) can be positioned arbitrarily in its work space. Rear leg has a rotational joint, and also has a relatively large active wheel at the tip of the leg. The joint axis is horizontal, and its movable range is over one round. Accordingly, the active wheel moves on a circular trajectory in the lateral plane. Totally, this configuration has ten degrees of freedom, and it is smaller number than that of a normal quadruped robot, twelve. On a flat terrain, four wheels are used for locomotion. Wheels contribute fast and efficient locomotion. When front passive wheel is positioned at just bellow the first joint axis, steering action is performed by controlling the first joint only. In addition, legs can function as active suspensions. In the case of rough terrain, the front passive wheels are locked, and front two legs are used to walk. Rear active wheels are still used for locomotion. The robot can generate traction at the all the contact points between the robot and the ground. When the robot encounters a large step where rear wheel can not climb, the rear leg is moved from the rear side to the front side through the air by leg joint motion. DC servo motors are used to drive the joints and rear wheels. Solenoids are used to lock the front wheels. Rotary encoder is attached at each joint and active wheel. In order to detect a step, the robot is equipped with an ultrasonic range sensor. The sensor head is attached at the tip of an arm that rotates around the vertical axis on the body. The altitude of the terrain around the robot is measured by the sensor. Control is performed by a personal computer.



Step mode

Conclusion

Man has made tremendous advancements in the field of machinery which is available in various forms and for various purposes. The majority of these machines involve locomotion and the predominant form of locomotion incorporated in these machines is the wheeled locomotion. Wheeled locomotion though being very versatile lacks certain specialized capabilities. Walking as a form of locomotion for machines is being explored only for the past few decades but still the achievements are far from perfection.
Bipedal walking especially is now a focus of fore front research as it poses a challenge in front of the technological capabilities of man. In developing robots to work in human environments, human like walking seems the most appropriate form of locomotion as the robot has to move around in an environment with obstacles and climb up and down stairs.

Research into walking robots has become increasingly important. As robots begin to move outside the controlled environments of laboratories and factories into the more dynamic environments, it is important that they are able to navigate through irregular terrain. Walking robots have a significant advantage over wheeled robots in that they can navigate over much more difficult terrain and adjust their stability to adapt to varying terrain conditions.

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