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Robot Locomotion – A Review

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Abstract

For a robotic machine to navigate through different geographical topographies, a platform having multi terrain maneuver capability is required. There are several types of designs available in the markets which make the robotic device capable of navigating through different terrains but their efficiency and performance is always a challenge due to differences in design specification for different natural terrains. The legged locomotion in hilly areas is favoredin the recent times, but the structural design and energy efficiency is always a challenge.In this paper meticulous analysis and summarization of some of the techniques including legged and all-wheel drive techniques has been discussed. Special focus has been given to locomotion in the hilly forest terrains including snowy and desert areas.

Key Words Legged locomotion, all-wheel drive, robotic device, multi terrain locomotion

1. Introduction

Robot locomotion is one of the important functions of the robotic device that helps the platform in traversing rough terrain; moving and interacting in human environment. Although wheeled locomotion is very common, foolproof, energy efficient and easily controllable;there are other motion alternatives are also available such as legged motion includingBi-pedal,Quadra-pedal, Hexa-pedal and so on. Track belt, walking, running, hopping, swimming, slithering, brachiating, etc. are the other forms that are used.According to Huang et al.[1], for a biped robot to walk on different geographical condition such as rough terrain, hilly areas etc., its feet portion should have enough mobility to maneuver.The actuator size and weights are the two most important constraints in developing the human size bipedal robot. Their research team proposed a method for planning walking patterns that include the ground conditions and actuator specifications primarily. Goswami[2]had proposed a method based on the importance of posture stability in the locomotion of bipedal robot. For a wall climbing robot,permanent magnetic tracks have been used for the locomotion of the robot for inspection of oil tank[3]. In a US patent [4], the Ronald and Eric has used a three-wheeled platform for the locomotion in which an omnidirectional wheel in combination with the conventional wheel was used for translational and pivoted motions. Hopkins et. al [5] has reviewed and discussed the advantages of the slithering locomotion (body undulation technique used by snakes) over their wheeled and legged counterparts. However this survey is meant for the extensive study of existing robot designs and a summarization of the various issues which could affect the future designs. This review paper attempts to discuss various multi-terrain locomotion designs in a reasonablemagnitude.

2. GAIT Locomotion

GAIT locomotion resembles human walking posture in autonomous biped, animals in quadruped, and insects in hexapod; and so on. The postural stability of a humanoid robot is a tough task while it is in motion, hence the GAIT locomotion can be incorporated in the legged robots. GAIT is human like walking posture which enables the legged robots to move in a more stabilized and balanced manner. McKenna et. al [6]has described the coupled oscillator model of GAIT coordination graphically by using dynamic locomotion simulator. The realistic motion of the limbs was produced by the stepping and stance motor programs in the simulator. A. Sprowitzet. al [7]presented a unique method in which the leg configuration is devised on spring loaded, pantograph mechanism with multiple segments. With the help of a simulation solution and experiments on a legged, trotting, quadruped robot; these researcher showed high speed locomotion on a flat terrain.

In GAIT locomotion, the spine is an important part as in the human body.The flexibility of the human spine is much higher and that is very difficult to achieve artificially. Khoramshahiet. al [8]has shown the effect of active spine and fixed spine in his research work. Their team compared the GAIT postures of both the actively controlled and rigid spine configuration.Their experiments showed that the actively controlled spine to be a more stable GAIT Pattern with distinct flight phase and double leg stances. The general GAIT features that need to be observed are sliding of the feet on the ground and directional stability. The best active spine showed a speed of 0.78 m/s in comparison to the rigid spine which showed a best speed of 0.68 m/s. Spine supports the overall body weight of the robot and it also helps in the coordination of the limbs. This limb coordination results in the accurate GAIT pattern, directional stability and body posture configuration.

Central Pattern Generators (CPG's) plays an important role in limb coordination. According to Paul and Jacques[9] the biped locomotion, say in human, has a tripartite system consisting of supraspinal input, spinal central pattern generating circuit and sensory feedback. CPG's play a dominant role as it is responsible for the sensory regulations. Gary and Gregory [10] had adopted a special technique named Cyclic Genetic Algorithm,used for the GAIT coordination in hexapods. They experimented on Stiquito, a six legged robot, developed by Mills[11] to test their technique which resulted in optimal tripod gait and enhanced speed; with a fast learning and capable algorithm. Stability can be classified into static and dynamic. The static stability can be defined as the stability when the robot has no motion at a particular moment of time. For a statical stability, a robot must have its center of gravity between its footprints.

A stable robot must have three points of contact at the ground and its center of gravity must lie in between the polygon made by the robot's footprint on the ground. A stable walking robot must have four footprints so that at any point of time during a walk, when one leg is in the air the polygon is shifted between the other three legs. Two legged walking robots, like humans, are also dynamically stable as the motion is supported by the spine, Central Pattern Generator (CPG) and the limb coordination.

The number of legs in the configuration determine the complexityof the limb coordination in the robot. The possible GAIT pattern is decided by the number of legs the robot has. For instance, if the robot has k legs the possible number of events 'N' will be [12]

$$N = (2k-1)!$$

For example, the possible event for a bipedal robot is 6; hence the more number of legs in the more the complex is the limb coordination problem. The leg configuration is discussed inthe coming sections in more detail.

2.1 Hopper or One legged robot

The least a legged robot can be is a one legged robot. It is also termed as a hopper because the only motion the robot can do is hopping as there is only one point of contact between the foot and the ground. The hopper can maneuver rough terrains and obstaclesin a stride by taking a steady start. The hopper's dynamic stability is the main point of concern as the robot has to balance its center of gravity by actively shifting its mass. Zhaohong Xu and others [13]studied the trajectory planning of a one legged multi-joint active hopping robot. They constructed a 6th order polynomial function over the 5th order to build a track based on its joint angle trajectory as shown in Fig. 2.

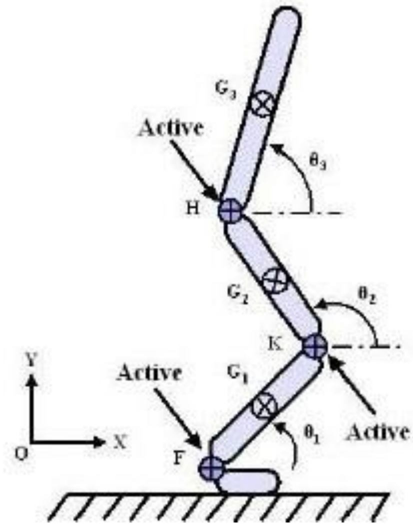

Fig.1: One legged multi joint hopper [13]

The experiment was conducted with a 3-DOF(Degrees of Freedom) rotary joint and four rigid bodies.They didnot use any elastic component such as damper, spring, hydraulic or pneumatic actuator etc. The plots between various attributes such as vertical position, joint torque, and joint angle were plotted against time which concluded with the development of a correction factor under unchanged boundary constraint conditions.

2.2 Two legged or Biped Robot

Two legged, often known as Humanoids, are the most common robots during the last decade. There are numerous examples available, out of which the most well-known and successful one is the HONDA ASIMO. It is a humanoid robot, 130 cm tall and weighing around 50 kg [14]. It has a walking speed of 2.7 KPH and a running speed of 7 KPH. It has 57 DOFs distributed all over the body. For e.g. Head has 3 DOF, Arms have 18 DOF and so on. TOPIO 3.0 [15] is a ping pong playing robot which was featured in the International Robot Exhibition, Tokyo. It is a humanoid robot made by a Vietnam company named TOSY. TOPIO 3.0 uses a processor and artificial neural networks with a 200 fps (frames per second) camera for its functioning. Apart from these, there are several other examples of humanoids such as Nao which competed in the soccer championship titled “Robocup”;Enona personal assistant and self-guiding robot.

Fig. 2: (a) Honda ASIMO [14] (b) TOPIO 3.0 [15] (c) Aldebaran Nao[16] (d) Fujitsu Enon[17]

A biped robot can walk, run, dance, jump, can go upstairs and downstairs but dynamic stability is still an issue in such bipeds. F. Plestan and others [18]established the viability of the theoretical control law. They validated a means to prove an asymptotically stable walking in an under-actuated planar, five link biped robot assuming a rigid contact model; where the swing leg impacts the ground and an instantaneous double support phase.Zero Moment Point[19] commonly abbreviated as ZMP is the point on the ground about which the summation of all the moments of the active forces will be zero. K. Mitobeet. al [20] applied the ZMP control law with the objective to obtain a smooth and clear motion in real time to two different biped robot validating them experimentally. They concluded that the efficient walking controlwas possible by providing a reference trajectory to the trunk position. S. Kajita and others [21] introduced a new method of biped walking by preview control of ZMP and demonstrated the effectiveness by a simulation of walking on spiral stairs. A cart-table model was used to represent the ZMP controller.A preview controller was designed to rectify the error generated by the difference in the simple cart-table and precise multi body models. One of the important features of bipedal design is that they can be like humans, in dimensions; which attracts the interest amongst the researchers particularly forthe human-machine interaction.

2.3 Three Legged or Tripod Robot.

Three legged or tripod is not common locomotion method as they don’t have their biological counterparts. Scientists from Romela Lab have developed a Self-excited tripedal dynamic experimental robot STriDER[22]. In thisrobot, a step indicates that two legs are acting as stance while the third one is swinging. The motion of the robot is done by pushing the center of gravity outside the body and covering the distance in a balancing action. The stability of the robot comes from its unique concept of actuated passive dynamic locomotion and it can also change its direction while walking.

2.4 Four Legged or Quadrupedal

AIBO was the first four legged dog robot designed in mid-1998[23] by Sony. AIBO means Pal or Partner in Japanese. AIBO was a robotic pet series, whose models were released every year untill 2005 in three generation phases. Some of the main features of the robot were the microphone which could record nearby sounds. It also had head sensors and altering lights than could show its emotions. Some more animal like four legged robots have been developed for the research on human-machine interaction. They can also be treated as pets for entertainment.An emotional bonding can also be developed to aid research on their responses with human interaction.

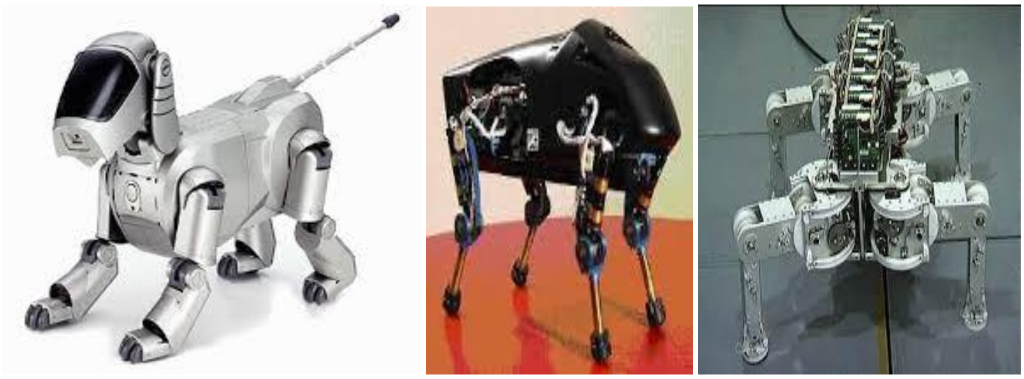

Fig. 3: (a) Sony AIBO [23] (b) DARPA BigDog [24] (c) TITAN VIII [25]

Big Dog [26], a more advanced quadruped robot developed by Boston Dynamics with the funding agency DARPA, is a multi-terrain robot powered by an engine. It is 3 feet long, 2.5 feet tall and weighs 240 lbs. Big Dog has over 50 sensors which include inertial sensors, joint sensors, acceleration, altitude, with a on-board computer processor and so on. It is usually driven by a human operator using an Operator Control Unit (OCU) with the help of IP Radios. It balances itself using an estimate of its lateral velocity and acceleration by sensed behavior of the legs and walks with the dynamically balanced trot gait[24].

TITAN VIII, was developed at the Tokyo Institute of Technology. This is another example of a four legged robot. It also uses dynamically stable trot gait pattern for its movement where two diagonal legs are lifted at the time of motion. Arikawa and Hirose [25] discussed the development of the robot; especially the leg mechanism by experimenting it with a one leg model. They haveremarked about its features like velocity, force and energy consumption.

The dynamic stability of quadrupeds has never been an issue as they are the most dynamically stable robots. According C. Queirozet. al [27], for the static stability of the quadruped, its three legs must be at the ground at any point of time for static gait. They studied the static stability of the four legged robot using a 2D+1 model which uses a robot description imposing some strong restrictions. They developed some exhaustive gaits for the same. The model describes the position of the toe with respect to the body.This model didn’t provide the information about the body posture and the height of the leg/s were also raised form the ground. The authors had described in detail an algorithm to find the stable sequence of the robot using the 2D+1 model.

2.5 Six Legged or Hexapod

Six legged robots are most stable and popular legged locomotion concept. The static stability in the hexapods is due to the use of the tripod gait in which at least three legs remain in contact with the ground at any point of time. The control complexity is reduced but the limb coordination is the main concern in the hexapods as the number of leg configuration isgiven by N = (2k-1)[12] which is equal to 39916800-a huge number. RiSE (Robots in Scansorial Environments) [28] is a biologically inspired six legged robot developed at Boston Dynamics in association with other technical universities and funded by DARPA. It is designed to climb the artificial surfaces such as wall, trees etc. either vertically or horizontally. The control and foot configuration has been developed to climb near vertical or vertical walls and biologically inspired by the insects.

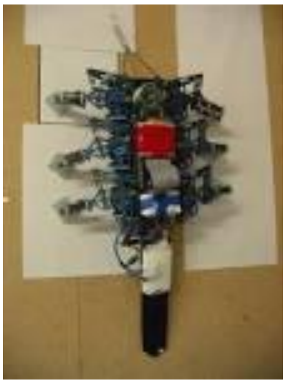

Fig. 4: Robots in Scansorial Environments (RiSE) [28]

In order to reduce the complexity in the limb coordination, the central control of the legged robots can be shifted locallyto each leg in order to control the locomotion. The joint controllers [29]can individually control the joints by determining the joint rotation angle of each joint. The leg controllers combinethe output of the individual joint controllers and set the footprint as per the input.Lastly the gait controller takes the output of individual leg controller.Therefore dividing the complex control issue into simple subsystems in turn makes it easier for the overall operation of the system.

2.5 Walking Control

The walking technique of legged robot is always a challenging task for the researchers. Pre-programmed robots can never successfully interact with the environment autonomously because they have to be reprogrammed for different environments.Hence, a self-learning technique must be incorporated to make the robot learn things as per its interaction with the outside environment. Rodney A Brooks at MIT in late 90’s developed Genghis [30], a robot which has reinforcement learning algorithm for walking. It can learn the coordinates by the movement of its legs. With the forward motion it has a positive result and negative with the crashes. Genghis learns with the reinforcement signals from sensors such as touch sensor, camera etc. Kimura and others [31] in their paper have discussed about the actor-critic reinforcement learning algorithm in which the actor with its stochastic policy and critic, estimate the evaluation function for the current policy.The actor improves the policy by using critic's temporal difference as an effective reinforcement. The architecture of the actor-critic reinforcement algorithm has been given in the figure 6 below.

3. Wheeled Locomotion

Wheel is one of the most popular and easy way of locomotion in mobile robots. The main reasons for this are their easy controlling, stability and simple mechanical design. Generally a mobile robot has a minimum of 3 Wheels (two wheels in rare cases) arranged in such a geometry by which the robot is stableduring the run. Wheeled locomotion is preferred over other modes of locomotion due to their power efficiency, faster running capability but traction on rough terrain, its control and stability are their primes areas of concern.

Wheels can be further classified as:

I. Simple Wheels or Standard wheels having two degrees of freedom i.e. around the center shaft and the point of contact.
II. Castor Wheels, generally used in trolleys etc., having rotation around the axis and the off-centric pivoted point.
III. Multi directional Wheels or Omni Wheels having three degrees of freedom achieved with the help of rollers mounted on the outer periphery of the wheels.

3.1 Concerns in Wheeled Locomotion

The major concerns in wheeled locomotion are:

3.1.1 Stability:

In order to achieve static stability, a robot must have at least two wheels in which the center of gravity lies below the axle center but dynamic stability is achieved only if the robot has three wheels or two wheels with a third point of contact at the floor and the center of gravity lies in between the support points.

3.1.2 Control:

Controlling in wheeled locomotion has always been a challenge. Straight driving requires only the control of powered wheels by locking the steering wheels straight. Omni wheels have high maneuverability and thus require a greater control over the speed and power distribution because a slight difference in the speed can make the robot to deviate from its path and make it difficult to control. Hence it can be concluded that the high maneuverability of the wheels (omni or multidirectional) are more difficult to control whereas simple or standard wheels can be controlled easily[12].

3.1.3 Maneuverability:

A multi-terrain robot must be able to maneuver swiftly in any direction on the ground. The steering wheels in general are idle and used only to maneuver the robot whereas the powered wheels don’t take part in the maneuvering, instead they follow. Inall-wheel drive robots, to support mobility, omnidirectional powered wheels are used which enhance the maneuverability in multi-terrain environments.

4. Other concepts

Legged and wheel locomotion are the most used robot locomotion mechanisms but recently there have been a development of new concepts which are actively taking their roles in in the locomotion of mobile robots.

4.1 Serpentine Locomotion

Snakes use ground points in order to push their body forward as a part of their locomotion system**.** Serpentine locomotion uses similar principle of creep for the forward movement of their body. Early credit goes to Shigeo Hirose of Tokyo Institute of Technology who studied the snake movement and designed ACM (Articulated Cord Mechanism).He developed ACM R3 [32] in 2000. This was the first snake robot which had 1 degree of freedom. Research is still going on the control and maneuverability of the serpentine locomotion but crawling seems to be a promising alternative in terrestrial locomotion.

Fig.5: Articulated Cord Mechanism Serpentine Robot R3 developed by Shigeo Hirose[32]

4.2 Legged Wheeled locomotion or Walking Wheels

This concept combines both the locomotion mechanisms i.e. legged and wheeled.,The legged locomotion can maneuver over rough terrains and stairs whereas the wheeled can maneuver on hard terrains with higher efficiencies. Hence, the idea was to develop a hybrid mechanism for using the advantages in both. For example Halluc II [33] of Chiba Institute of Technology has 8 legs equipped with wheels and three different types of mobility transformation including drive-mode switching between wheel-cruising and leg-walking to offer superior mobility performance.

Fig. 7: Halluc II developed in Chiba Institute of Technology[33]

4.3 Track Belt/Slip Locomotion

Omni Directional wheelshave their distinct advantages but their control is the major concern.However, wheeled locomotion has disadvantage while operating in loose terrain or where the wheels cannot overcome the gapswhich are bigger than the wheel size.Hence, track belts were introduced to increase the efficiency of the wheel locomotion in loose and rough terrains. A track belt locomotion robot usestank type track belts which offer great dynamic stability due to its larger surface area in contact with the ground at any point of time.Hence, the traction of robotic device is far better in loose surfaces than any other mode of locomotion. To change the direction, the robot has to differentiate the speed of the tracked wheels or just reverse their motion.It also needs a larger area in order to completely change its orientation in the ground. Aurora Automatika[34]is a tracked robot built by Hagen Schempf in Pennsylvania which is designed with a single track belt locomotion. The system was built with a flexible elastomeric mono-belt with a central drive- and guide spine, which when flexed, forces the tread into a shape allowing it to steer. Similarly SNR1 of the National Institute of Advanced Industrial Science and Technology (AIST)[35] has capability to climb, uphill and staircases with the help of a single track along the wheels.

Fig. 8: (a)Aurora [34] of Hagen Schempf (b) SRN1 [35] of AIST using Track Belt Locomotion

5. Conclusion

The paper reviews and summarizes some of the best locomotion techniques used in mobile robots for the locomotion in rough, uneven and loose terrains. It can be concluded that there is not a single mechanism that can maneuver over all geographical terrains but researchers have done quite a significant development in legged and wheeled mechanisms. The design of the locomotion mechanism is chosen according to the application of the robot which varies based on different topologies.Hence, there is no mechanism which is superior to the other. However, it will be possible to build a mechanism which can be easily varied according to various terrainsif focus is given on to characteristics like stability, energy efficiency and control maneuverability.

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