（千葉大学学位申請論文）

# 油圧駆動型6脚ロボットの不整地歩行のための力制御とインピーダンス制御に関する研究

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# ABSTRACT

A variety approach of multi-legged robot designs, especially on a large scale design with hydraulically driven actuators exist, but most of it still unsolved and used primitive techniques on control solutions. This made this area of research still far from demonstrating the scientific solutions, which is more towards developing and optimizing the algorithm, control technique and software engineering for practical locomotion (flexibility and reliability). Therefore in this thesis, the study is done to propose two categories of solution for statically stable and hydraulically driven hexapod robot, named COMET-IV, which are dynamic walking trajectory generation and force/impedance control implementation (during body start patching), in order to solve the stability problems (horizontal) that encountered when walking on extremely uneven terrains. Only three sensors are used for control feedback; potentiometers (each leg joint), pressure sensors (hydraulic cylinders) and attitude sensor (center of body). For dynamic walking trajectory generation, the fixed/determined of tripod walking trajectory is modified with force threshold-based, named as environment trailed trajectory (ETT), on each first step of foot during support phase (preliminary sensing uneven terrain surfaces). Moreover, the proposed dynamic trajectory generation is then upgraded with capability of omni-directional walking with a proposed center of body rotational-based method.

The instability of using the ETT module alone and with proposed hybrid force/position control in the previous progress, during body patching on walking session is then solved using the proposed *pull-back* position-based force control (PPF). PPF controller is derived from the ETT module itself and supported by proposed compliant (switching) mechanism, logical attitude control and dynamic swing rising control. The limitation of PPF controller applied with ETT module for walking on uneven terrain contains extreme soft surface makes the study narrowed to the impedance control approaches as a replacement of PPF controller. Three new adaptive impedance controller are designed and proposed: Optimal single leg impedance control based on body inertia, Optimal center of mass–based impedance control based on body inertia and Single leg impedance control with self-tuning stiffness. To reduce the hard swinging/shaking of the robot's body in motion that arise after applying the proposed impedance controllers, fuzzy logic control via Takagaki-Sugeno-Kang (TSK) model is proposed to be cascaded on the input feedback of the controller.

The study has verified the effectiveness of both categories of control unit (dynamic trajectory, force controller and impedance controllers) combination throughout several experiments of COMET-IV walking on uneven/unstructured terrains.

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# ABBREVIATIONS

**A/D**. Analog to Digital

**BCS**. Body Coordinate System

**BMC**. Body Mass Coordination.

**CNN**. Cellular Neural Network

**CoG**. Center of Gravity.

**CoM**. Center of Mass.

**CoP**. Center of Pressure

**COMET**. Chiba University Mine Electronics Tool.

**CPU**. Control Processing Unit

**D/A**. Digital to Analog

**DH$_0$**. Dyanamic $H_0$

**DOF**. Degree of Freedom

**ETT**. Environment Trailed Trajectory.

**ETT-PPF**. PPF controller with ETT

**ETT-PPF-LTLD-LBA**. PPF controller with ETT and LTLD-LBA scheme

**FLC**. Fuzzy Logic Control

**GA**. Genetic Algorithm

**GWALR** Grid-based Walking Assistant for Legged Robot

**LAImp**. Single Leg Impedance

**LBA**. Logical Body Attitude

**LQR**. Linear Quadratic Regulator

**LRF**. Laser Range Finder.

**LTLD**. Logical Terrain Level Detection

**MAImp**. Center of mass—based Impedance

**MISO**. Multi-Input Single-Output

**MLP**. Multilayer Perception

**NARX**. Nonlinear Autoregressive with Exogenous Input

**NN**. Neural Networks

**PFAC**. Position/Force/Attitude Control

**PID**. Proportional, Integral and Derivative

**PPF**. *Pull-back* Position-based Force

**SCS**. Shoulder Coordinate System

**STImp**. Selft-tuning Stiffness Impedance Control

**TSK**. Takagaki-Sugeno-Kang

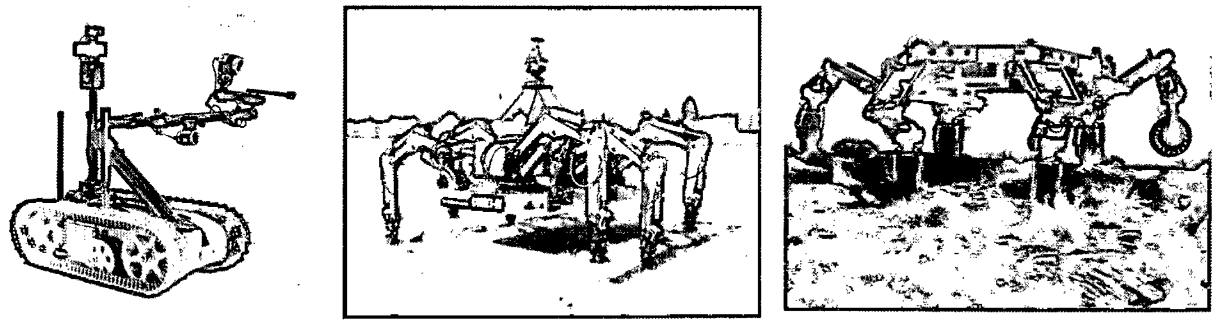
**ZMP**. Zero Moment Point

# Chapter 1

# Introduction

## 1.1 Research Background

Ground robot is one of the major areas of research in robotics engineering and it consists of several types of robot configurations, namely, legged robot, wheeled robot and mixed legged-wheeled robot (hybrid), and examples of such robots are shown in **Figure 1.1**. From mechanical point of view, wheeled robot is easy to implement compared to legged robot when profound stability is not a problem. However, legged robot or walking robot still have strong role to play, especially in surroundings that are life-threatening to humans, on terrains with high degree of inclination and areas that have been hit by a disaster; all these situations will require the use of robust unmanned robot system to assist their human counterparts in conducting specific tasks. It is almost impossible to utilize wheeled robots in the situations above, unless the configuration of the robot is modified into the mixed legged-wheeled type as shown in **Figure 1.1(c)**.



**(a)** **(b)** **(c)**

**Figure 1.1:** Ground robot; (a) TALON[1], (b) COMET-IV (c) ATHLETE-NASA[2]

On the contrary, stability needs special considerations when working with legged robots, though the problems related to stability can be solved mechanically, electronically or using specialized computer software but, in actuality, all these solutions must be employed in the complete development of the robot. The Chiba University Operating Mine Detection Electronics Tools (COMET) [3], mainly employed in a wide range of life-threatening tasks such landmine detection and search and rescue operation, is used as a platform for this study. The latest version of the robot, COMET-IV as shown in **Figure 1.1(b)**, is hydraulically driven while its size is three times bigger than the previous versions and is targeted to have the ability to walk on large-scale uneven area such as mountainous area and after-quake area. The research objectives of this study are as follows [3]:

- Able to walk in all directions (omni-directional).
- Able to walk with speed up to $1km/h$.
- Able to step over obstacles up to $1m$ high (uneven terrain).
- Able to walk on sloped terrain up to $20^0$ of inclination.
- Able to be remotely controlled via Tele-operation system.
- Able to walk autonomously with obstacles avoidance system.

In this study, since the mechanical structure of COMET-IV has been completed, the focus is on the design of control and algorithm to enable the robot walk on uneven terrain by taking as many advantages as possible of its current structural configuration.

## 1.2 Research in Robot Locomotion: The Motivation and Mechanisms

Since last century, artificial systems and robots resembling human beings or animals have been developed to improve the quality of human life with regards to, among others, working hours, home conveniences and public services. Considerable research has been devoted to design and develop artificial systems that can mimic human beings or animals, and walking robots, wheel robots, marine/swimming robots, and flying robots are examples of artificial systems that have been recently developed.

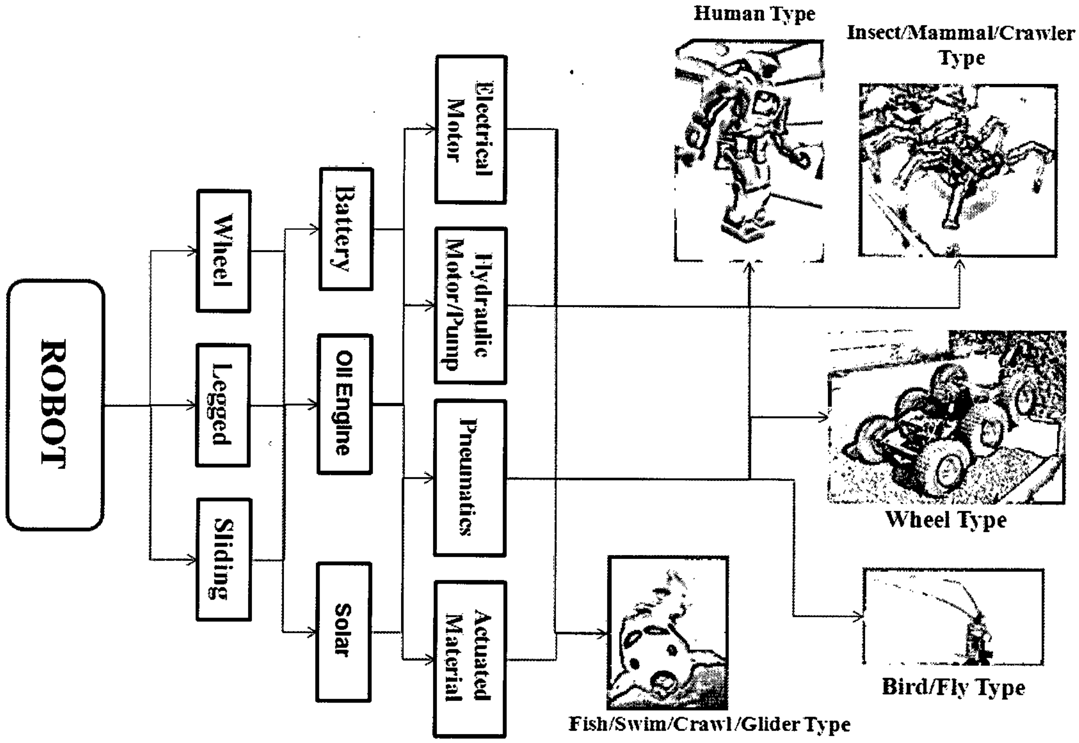
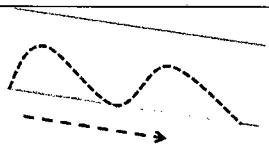
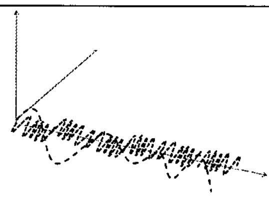
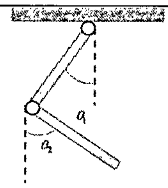
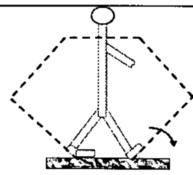
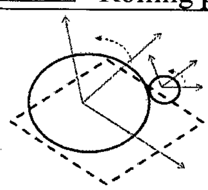



**Figure 1.2:** General robot design divisions and types

As shown in **Figure 1.2**, each type of robot could be designed to operate autonomously, known as mobile robot, or to be remotely controlled via a human operator. Different types of robot are explored and researched differently since its design is based on the corresponding applications and the environment they have to operate. For example fish/swim/glider robot is mainly for surface or underwater applications while bird/fly robot is mainly for flying mission such as used in field monitoring. In this field of research, the study is commonly carried out in two parts before the final integration is done, namely, motion control and vision recognition. Each part will have different amount of influence on the robot's operation depending on the structure and configuration of the robot. However, motion control is a major part in robot design and development as vision recognition is used only to support and direct the robot's motion. However, this study is limited to the situation when the robot touches the surface of the terrain.

**Table 1.1:** Locomotion mechanism based on life form creature [4]

| Type of Motion | Resistance of Motion | Basic Kinematics of Motion |
|---|---|---|
| Flow in Channel | Hydrodynamic/ Aerodynamic forces |  Eddie's |
| Crawl/Sliding | Friction forces |  Vibration |
| Running/Jumping | Loss of kinetic energy |  Oscillator movement of multi-DOF |
| Walking | Gravitational Forces |  Rolling polygon |
| Rolling | Moment of Inertial and gravitational forces |  Altitude/Longititude and rolling polygon |

Different types of mobile legged robot have different motion mechanisms depending on the structure configuration of the robot. The basic kinematics of motion for different types of motion corresponding to natural creatures is summarized in **Table 1.1.** Seigwart *et al.* (2004) in their book has outlined three core issues in robot locomotion study: stability, characteristics of ground contact and type of environment. In legged or walking robot research area, many issues have been outlined to improve the performance of the robot in order to achieve lifelike walking behavior similar to the targeted life form. In researches involving biped robots that are based on human body, better dynamic locomotion became a main issue in motion control. Park (2002) in his articles mentioned that good biped robot should have the following capabilities: accurate trajectory tracking, maintaining a good balance and posture of upper body, stable footing and adaptable to various environmental conditions. However, the design issues are different for robots that are based on mammal's legs or insect's legs (> 3-legs) as the importance of dynamic stability decreases with increasing number of legs. Rebula *et al.* (2007) has outlined the control issues that need to be tackled in the development of stable animal type walking robot as follows: impassable terrain, foot slippage, accidental collision, modeling errors and sensor errors. As an example, the research on a quadruped robot named *Boston Dynamics LittleDog* has focused on the robot's capability to walk on unpredictable terrain environment that includes rough terrain environment [5, 6], also on its ability to cope with external disturbances, such as being pushed by other objects, and when placed on being slippery surface/edge [7]. The stability problems above could be solved by applying the combination of the proposed force control and stability control on the robot, and the solution should include a vision unit (precision factor).

Another issue that arises in legged robot's control design and development is the scale of structure (size and weight) and the prime mover. From size and capacity point of view, robots such as ROBOCLIMBER [8], MECANT [9] and TITAN [10] are different from the SILO [11], AMRU [12] and LittleDog [6]. Also, the prime movers used in all the robots reported in [3], [8], [9], and [10] are gasoline engine, cylinder pumps and hydraulic motors while that in the robots reported in [6], [13] and [14] mainly use electric motor as actuators. Consequently, different approaches are used to solve the robot's stability problems. As reported in [3], [8], [9], and [10], most of the large scale legged robots are designed for extremely uneven terrain such as a mountainous environment, slopes with high inclination, extremely soft ground (wet soil, sand soil, etc.) and after-disaster area (such as caused by earthquakes and tsunami).

## 1.3 The Practical of Legged Robots

One of the favorite research areas in the field of ground robots is the legged locomotion robots. As previous discussed, this type of artificial system is designed to mimic a walking creature, especially human being (commonly named bipedal robot or humanoid) since a human being is more stable and flexible compared to other walking creatures.

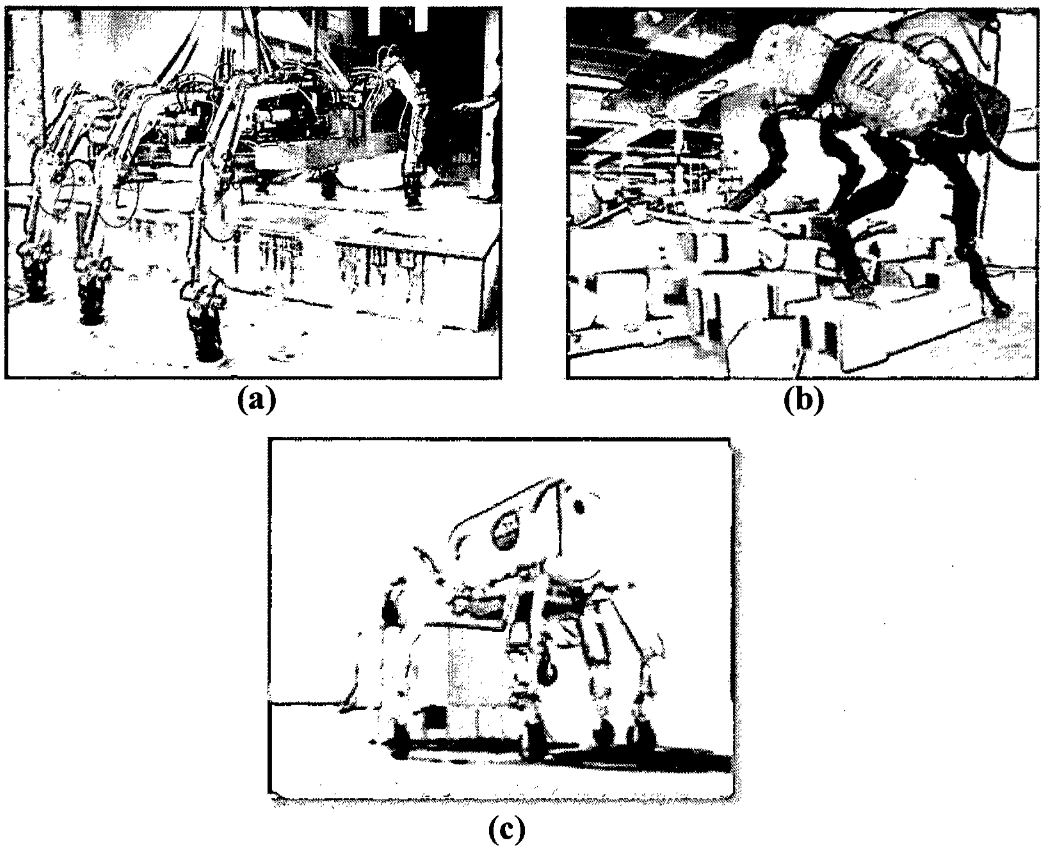


**Figure 1.3:** Example of legged robots walking over the extreme cliff/obstacle that is impossible to achieve with wheel robot (Snapshots of ;(a) COMET-IV,(b) BigDog(c) ATHLETE-NASA)

Though currently most of the studies carried out on ground robots are the wheel-type, the legged locomotion type still have some advantages especially in situations where the robot needs to step on/over obstacles in its path (using force feedback or vision), as shown in **Figure 1.3**, or when the robot needs to rapidly maneuver over a variety of minor obstacle (depending on the designed structure) with minor body inclination.

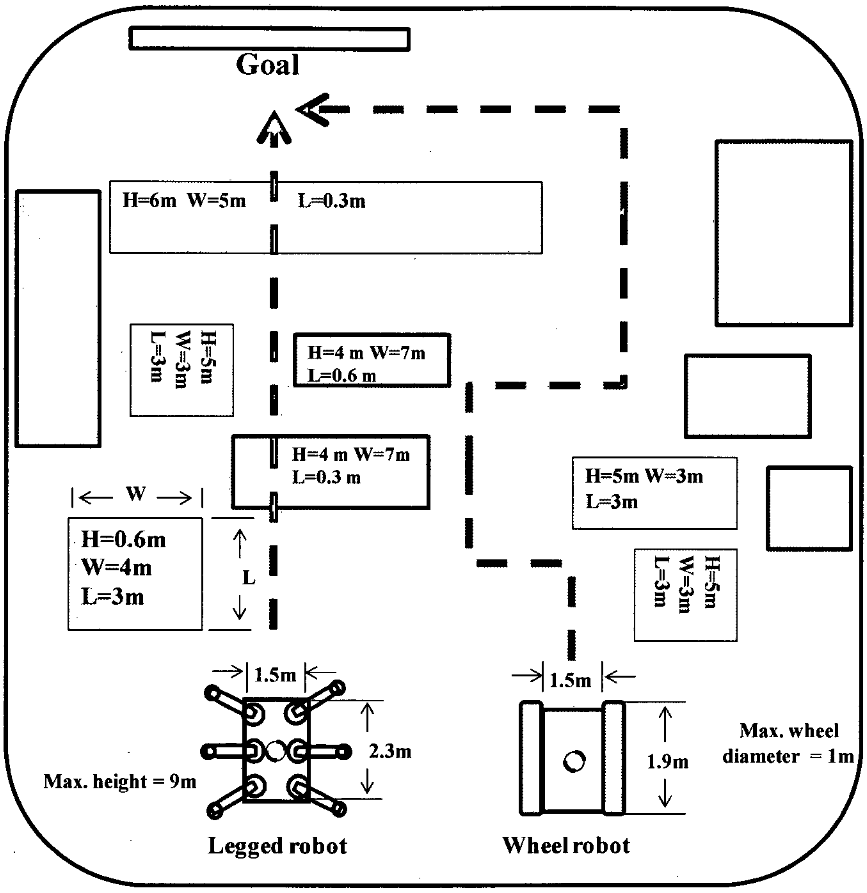



**Figure 1.4:** Example of situation that shows the practicality of legged robots application if compared to the wheel-type robot (red line boxes are prohibited to be touched/stepped on)

On the other hand, if compare to wheel-type robot, legged robot has minimum contact with the ground, thus, make it capable to avoid any prohibited ground surfaces, such as walking through the mine area, after-quaked area etc. Moreover, this kind of robot is capable of stepping through the obstacles (if those obstacles lower than its maximum body height position) rather than turn over to avoid. With this capability, locomotion path for legged robot is possible to be minimized. As example situation as shown in **Figure 1.4**, wheel robot needs to pass through some path that suite to is overall size, but legged robot (same payload capability) capable of passing through the obstacles as long as the obstacle height (*H*) less than its maximum height position (if the obstacle are prohibited to be stepped on) and the pit between those obstacles fitted to its leg/foot sizes.

## 1.4 Principle and Factor of Stability for the Legged Robots

Stability became a major issue for mobile robot and it corresponds to the mechanisms that have been applied to the robot. The major part that attribute to the stability of a robot are the number/geometry of contact points, robot center of gravity/pressure/mass, the degree of inclination of terrain (ground) and resistivity of pressures by flow of medium (air and water). The stability criterion for legged robot is divided into two categories: statically stable and dynamically stable. Increasing the number of legs on a robot structure will increase its static stability but will decrease its dynamic stability, and vice-versa, as shown in **Figure 1.5**.

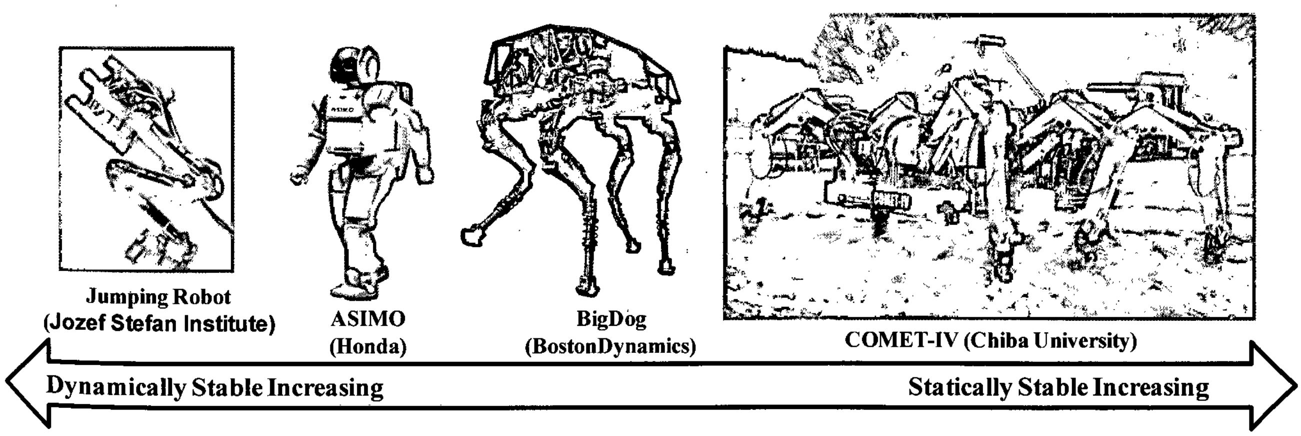



**Figure 1.5:** Legged robot's stability criterion