DESIGN AND ANALYSIS OF A HYBRID LOCOMOTION SYSTEM FOR MOBILE ROBOT

QADIR BAKHSH JAMALI

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Faculty of Mechanical and Manufacturing Engineering
UNIVERSITI TUN HUSSEIN ONN MALAYSIA
86400 Parit Raja, Johor

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ABSTRACT

Mobile robots are defined as autonomous mechanical device, which performs automated tasks either by predefined program or under human guidance by using remote control devices. The use of mobile robots is limited due to the lack of an effective locomotion system. There are few kinds of locomotion mechanism used in mobile robot such as wheel, track and leg. A major unresolved issue for most industrial and other applications is to complete the task in the various terrains such as stairs, smooth and rough path etc. This study proposed a new design of hybrid locomotion system for mobile robots. It is the combination of wheel and track type locomotion system resulting as a hybrid mechanism that includes a flexible and versatile interchangeable locomotion. A 3D virtual model was designed in CAD software. For smooth transformation a new switchover module called track tensioner unit that facilitates the engaging and releasing of track mechanism was developed and included in the system. The three wheeled locomotion mechanism used in this system would enable the robot to move on flat path at reasonable high velocity and maneuverability. The track system provides very reliable robot mobility on rough terrain. To ensure structural integrity, several selected parts of model were analyzed to ascertain their mechanical behavior under static load condition by using Solidworks simulation tool. From literature reviews, two type of materials namely Aluminum alloy AL6061-T6 and Aluminum alloy AL7075-T6 were short listed. The stability of these materials was then further analyzed using finite element method according to the current design specifications. The results proved that Aluminum alloy AL7075-T6 to be more suitable for this type of mobile robot.

ABSTRAK

Robot bergerak ditakrifkan sebagai alat mekanikal autonomi, yang melakukan tugas-tugas automatik sama ada melalui program yang telah ditetapkan atau di bawah bimbingan manusia dengan menggunakan alat-alat kawalan jauh. Penggunaan robot bergerak adalah terhad disebabkan oleh kekurangan sistem pergerakan yang berkesan. Terdapat beberapa jenis mekanisme pergerakan yang digunakan dalam robot bergerak seperti roda , trek dan kaki. Isu utama yang belum selesai bagi kebanyakan industri dan lain-lain aplikasi adalah untuk melaksanakan tugas di permukaan yang pelbagai seperti, ditangga, permukaan yang licin, yang kasar dan lain-lain. Kajian ini mencadangkan satu reka bentuk baru sistem pergerakan hibrid untuk robot mudah alih. Ia adalah gabungan roda dan jenis sistem gerakan trek sebagai mekanisme hibrid yang fleksibel dan serba boleh. Model maya 3D telah direkabentuk menggunakan perisian CAD. Bagi melancarkan transformasi satu modul pengubah baru yang dipanggil trek unit "Tensioner" bagi memudahkan menarik dan melepaskan mekanisme trek telah dibangunkan dan dipasang pada sistem. Mekanisme pergerakan tiga roda yang digunakan dalam sistem ini akan membolehkan robot bergerak di atas jalan rata pada kelajuan yang tinggi dan mudah dikendalikan. Sistem mekanisme trek memberikan prestasi robot yang sangat baik di jalan kasar. Bagi menjamin kesahihan integriti struktur, beberapa bahagian model dipilih dan dianalisis untuk mendapatkan kelakuan mekanikal mereka pada keadaan beban statik, menggunakan alat simulasi Solidworks. Daripada kajian literatur, dua jenis bahan iaitu Aluminium aloi AL6061-T6 dan Aluminium aloi AL7075 -T6 telah dikenalpasti. Bahan-bahan ini kemudian dimodelkan pada sistem hibrid ini dan dianalisis menggunakan kaedah unsur terhingga. Hasilnya menunjukkan bahawa, aloi Aluminium AL7075 -T6 adalah lebih sesuai untuk reka bentuk robot bergerak ini.

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LIST OF ABBREVIATIONS

CAD	Computer Added Design/Drafting
3D	Three Dimensions
AL	Aluminium
USAR	Urban Search and Rescue
DCS	Direct Control System
CNC	Computer Numerical Control
PLC	Programmable Logic Control
RFID	Radio Frequency Identification
DOF	Degree of Freedom
STRV	Shape Shifting Tracked Robot Vehicle
CoMoRAT	Configurable Mobile Robot for All Terrain
ATV	All-Terrain Vehicle
TTU	Track Tensioner Unit
SS Curve	Stress-Strain Curve
DC	Direct Current
ESTRN	Equivalent Strain
FOS	Factor of Safety

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1 **Comparative study between wheeled and tracked mobility system for Mobile robot**
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Applied Mechanics and Materials vol. 393 (2013) pp 538-543
(SCOPUS, EI and ISI Proceedings)

2 **New Hybrid Locomotion System Design**
Khalid Hasnan, Qadir Bakhsh, Aftab Ahmed
Australian Journal of Basic and Applied Sciences vol. 8 (2014) pp 247-252
(ISI Indexed)

3 **Industrial Automation and Manufacturing Systems: Concepts & Applications**
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Advanced Materials Research vol. 903 (2014) pp 291-296
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4 **Integration of Value Stream Mapping with RFID, WSN and ZigBee Network**
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Applied Mechanics and Materials vol. 465 (2014) pp 769-773
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Aftab Ahmed, Khalid Hasnan, Winardi Sani, Qadir Bakhsh
Australian Journal of Basic and Applied Sciences vol. 8 (2014) pp 662-668
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6 **Study of RFID application with Zigbee Network in supply chain management**
Khalid Hasnan, Aftab Ahmed, Qadir Bakhsh
In: Proceedings of the International Conference on Mechanical, Automotive and Aerospace Engineering (ICMAAE 2013), 2-4 July 2013, Kuala Lumpur

7 **Design and Failure Analysis of Track Tensioner Unit for Mobile Robot using Solidworks**
Khalid Hasnan, Qadir Bakhsh, Badrul Aisham, Aftab Ahmed
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2 **International Conference on Advances in Mechanical Engineering ICAME-2013.** *Organized by: UiTM at Melaka Malaysia on August 28-29, 2013.*

3 **2nd International Conference on Engineering and Technology ICET-2013**
Organized by: TATIUC at Bali Indonesia on December 12-13, 2013.

4 **2nd International Conference on Robotics, Automation Systems ICoRAS-2013**
Organized by: TATIUC at Bali Indonesia on December 12-13, 2013.

5 **4th International Conference on Mechanical and Manufacturing Engineering ICME-2013.** *Organized by: UTHM at Putra Jaya Malaysia on December 17-18, 2013.*

6 **5th International Conference on Mechanical, Industrial and Manufacturing Technologies MIMT-2014.** *Organizing by: International Association of Computer Science & Information Technology (IACSIT) at Penang Malaysia on March 10-11, 2014.*

7 **International Conference on Mathematics, Engineering and Industrial Applications ICoMEIA-2014.** *Organizing by: UniMAP and IIUM at Penang Malaysia on May 28-30, 2014.*

8 **International Conference on Mechanical Engineering and Industrial Manufacturing (CMEIM-2014).** *Organizing by: International Association of Computer Science and Information Technology (IACSIT) at Nanjing, China on June 27-29, 2014.*

CHAPTER 1

INTRODUCTION

Product quality, rate of productivity, product runtime and customer satisfaction are the main considerations of any industry. Modern production processes use industrial automation systems, because it results high efficiency and high quality production (Bayindir & Cetinceviz, 2011). Industrial robot is a mechanical or virtual intelligent device and it is one of the automated systems usually used where repeatability of process, material handling and time consumption are required (Vidoni *et al.*, 2011). Robots can be autonomous, semi-autonomous or remotely operated an electromechanical machine that is run by computer programming. In industries most of the robots have a fixed base or station that limits their capability and feasibility. Mobile robots are expected to be a solution for a vast range of applications from service robots, e.g. in hospitals, domestic cleaning, at airports or railway stations to industrial applications. Their uses resolve two fundamental problems, i.e. material handling and reduction in manpower.

1.1 Background

Mobile robot technology is moving through advance and matured level, where it should soon be possible to use robust, portable mobile robots for military, surveillance and Urban Search and Rescue (USAR) applications (Bakhsh *et al.*, 2013). In hazardous and unsafe environments for human, mobile robots may be used, in either indoor or outdoor environments. The human search and rescue is one important application of mobile robots in emergency situation caused by natural and man-made disasters. These robots can co-ordinate in various tasks, search the affected area, locate and identify the victims from rubble, report their conditions to control room and deliver first aid. The survival rate will be high, if survivors can be rescued and receive treatment immediately after the disaster occurs (Hasnan *et al.*, 2014). Therefore, rescue activities should be carried out quickly and robots can effectively help people deal with these dangerous environments, thus reduce the risks that the associated personnel will be exposed to.

1.1.1 Classifications of mobile robot

Nowadays, robots do lot of different tasks in many fields and number of jobs handled by robots is growing steadily. There are four main types of mobile robots (Bekey, 2005) such as;

- Humanoid
- Unmanned ground vehicle
- Unmanned aerial vehicle
- Autonomous underwater vehicles

1.1.2 Applications of mobile robot

Mobile robots are used for many tasks and operations in industries, domestic and commercial purposes (Bekey, 2005). The various types of application are listed below;

- Industries
- Military/ Defense
- Surveillance
- Urban search and Rescue
- Bomb disposal
- Space exploration
- Hospitals
- Laboratory research
- Domestic

1.2 Problem Statement

The use of robot is increasing very rapidly in various applications, similarly mobile robot also familiar in numerous applications i.e. Industry, military, rescue, domestics etc. But still there is lacking of an effective and flexible locomotion system for mobile robot. That caused the mobile robot unable to move in multi environments i.e. steps, stairs, and rough surface.

1.3 Aim of Study

The aim of the research study is to design a hybrid locomotion mobile robot that will be able to work under various terrain environments, utilizing interchangeable mobility characteristic.

1.4 Objectives of study

The main aim of this study was to design a wheel and track hybrid locomotion system for mobile robot, with interchangeable mobility characteristic. Based on the research gaps identified in literature review, this study has the following objectives;

- To design a virtual mobile robot with interchangeable multi locomotion system i.e. Wheel and Track.
- To optimize the mechanical behavior of the robot, the selective parts are analyzed under static loading and to recommend the suitable material according to the design requirement.

1.5 Scope of study

The scope of study covers the design of mobile robot locomotion mechanism. This study is helpful for the use of proper mobility system of mobile robot to work in multi environments either structured or unstructured path. The study would include the design of 3D modeling, design analysis of parts under static load condition and selection of suitable material for robot design.

1.6 Research Motivation

Due to the advances in the technology, the use of robotic system in various applications is become very familiar and interesting because, it makes things easier for humans according to their requirement. The motivation for this study was that a system can be design or developed for mobile robots, which work in multi environments.

The Figure 1.1 summarizes the existing problem in mobile robot, its proposed solution and outcomes.

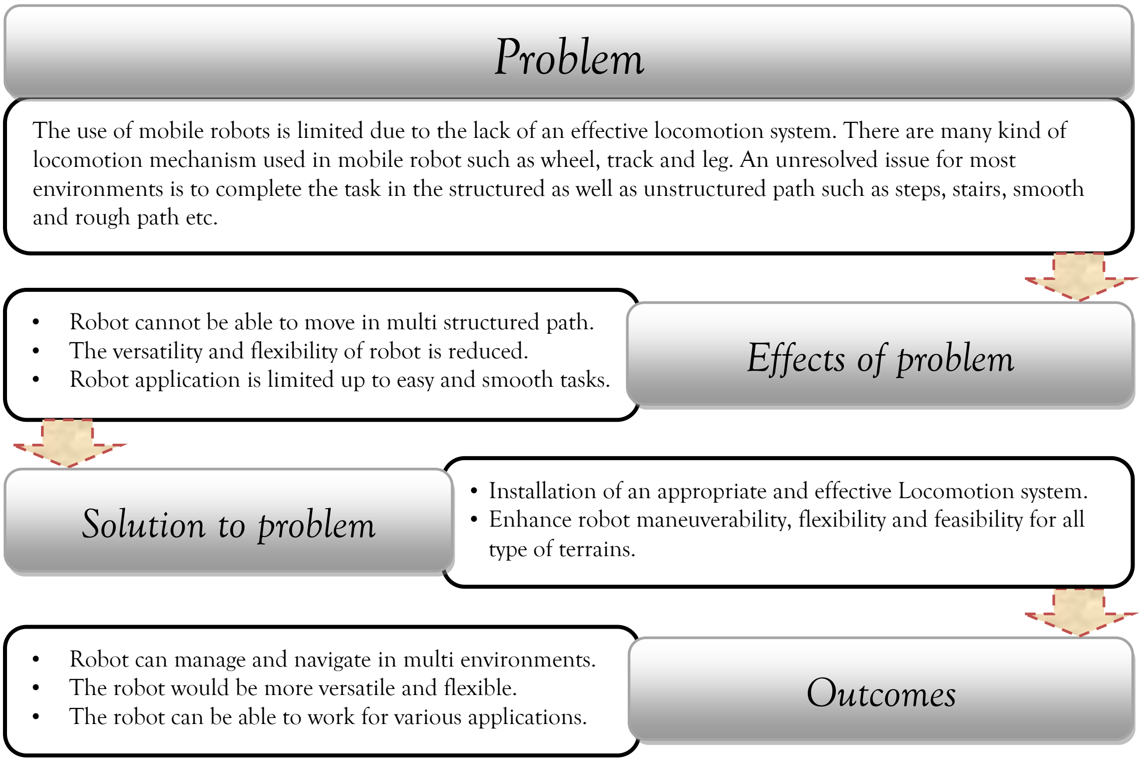

Figure 1. 1 Research Motivation

Mobile robots have vast applications such as rescue, urban search, miltiry, industries, survilelnce and domestic purpose. Mobile robot should be flexible, versatile, stable and feasible for all type of environments. An improper locomotion system results in the limitation within specific environments, such as smooth and easy path. Therefore the mobile robot is unable to move in multi terrains and various environment. To overcome this problem an effective locomotion system was selected and designed, which enhance robots mobility performance.

1.7 Contributions towards robotic field

The proposed design for mobile robot would provide solutions towards the series of major problems related to its design and function, i.e. operating on unstructured terrains. The major contributions are;

- A new design for mobile robot with interchangeable locomotion system where the robot can work either on wheel motion mechanism or track or on both as a hybrid system.
- The track tensioner unit enhance the track tension and suspension mechanism, whereby the mobile robot would be able to move through various types of obstacles, such as smooth path, steps, inclined path and unstructured path.
- Design and analysis of virtual model in CAD software also reduce the actual prototype fabrication time consumption and cost. It also gives the optimum solution for the selection of appropriate design parameters that includes dimensions, material, environment and component failure.

1.8 Thesis layout

This thesis is organized as follows; Chapter 2 present the study of existing works in several key areas of robotics research and background to the field of mobile robots along with examples of existing types of design architectures. It also highlights the existing issues related to wheel and tracked mobile robots, their locomotion related problems. Chapter 3 describes a step by step explanation of research methodology. The research methodology flowchart, which presents the type of activities carried out, tools used for achieving the target and provides the solution. Detailed mechanical design of the hybrid mobile robot is also described in this chapter. Chapter 4 provides the analysis of mechanical behavior for the model parts in order to study the robot functionality and selection of the suitable material for mobile robot. The final conclusion remark of this study is described in Chapter 5 together with the recommendations.

CHAPTER 2

LITERATURE REVIEW

Many efforts and research have been carried out in recent decades, for the use of mobile robots in various applications. They have provided solution for a variety of applications, for example, in defense, rescue, surveillance, bomb disposal, hospitals, domestic, airport and industrial. A proper and appropriate motion mechanism and flexible locomotion system is required to make the mobile robot more versatile and feasible for different applications. Sometimes the working environment is very complicated, including not only high obstacles and deep trenches but also narrow palisades and floors littered with rubble such as in urban search and rescue applications. Consequently the robot should have rich configurations, which can be compatible for various tasks and complex environments.

2.1 Automation

This technology is used to optimise the material dispatch or handling system by the help of machines, control systems and information technologies. The major benefits for introduction of automation in industries is to enhance the rate of workdone, accuracy, minimze the material transportation cost and time as compared to manual labour (Sattar *et al*., 2014). It highly reduces the requirement of human skill and mental approach, while increase in workload, speed and repeatability. In Figure 2.1, the different types of automation mostly used for various applications are shown.

In the industries, the automatic control system enables a safe, profitable and high production process (Bayindir & Cetinceviz, 2011). An established system must trade off between the involved fixed costs for advanced equipments and the reduction of the variable costs for energy consumption (Pellicciari *et al*., 2013).

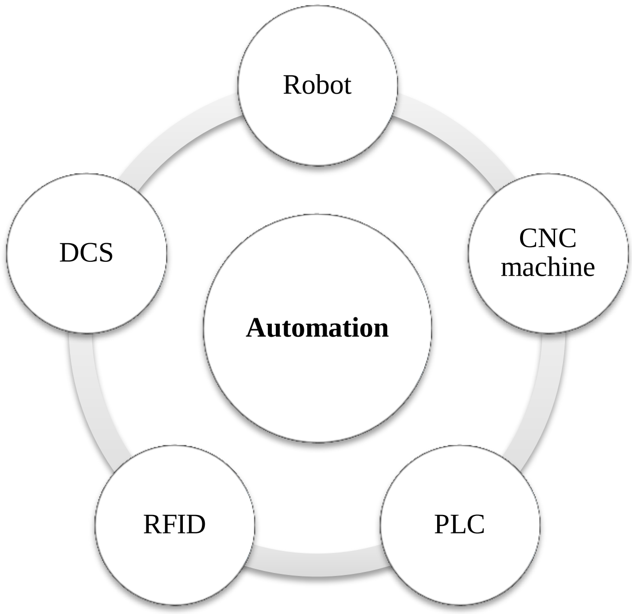

Figure 2. 1 Types of Automation (Sattar *et al*., 2014)

2.2 Robots

Robot is defined as autonomous mechanical device, which performs automated tasks either by predefined program or under human guidance (Defever *et al*., 2004). The robots are mainly used as alternative to humans being to perform difficult, dirty and dangerous tasks. The industrial robots are used in specific range of applications, because most of the industrial robots are stationary and operated with a fixed base (Goris, 2005). Those fixed base robots perform some industrial tasks such as welding, painting, drilling, packing, assembly and material transporting. According to Bekey (2005), there are many types of robot used now-a-days in industries, military, rescue, surveillance and domestics; some of them are shown in Figure 2.2.

(David Remy *et al*., 2011)

(Nam-Su & Dong-Soo, 2008)

(Roan *et al*., 2010)

Figure 2. 2 Types of Robot

2.2.1 Advantages

There are many advantages of robots concerned with different applications. Few advantages are listed below (Kuttan, 2007);

- Greater flexibility
- Re-programmability
- Greater response time to inputs than humans
- Improved product quality
- Accident reduction
- Reduction of hazardous exposure for human workers

- Automation less susceptible to work stoppages

2.2.2 Disadvantages

Beside the rich advantages of the robots, it also deals with few disadvantages (Kuttan, 2007 and Niku, 2001) such as;

- Replacement of human labour
- More unemployment
- Advertised technology does not always disclose some of the hidden disadvantages
- Hidden costs because of the associated technology that must be purchased and integrated into a functioning cell.

2.2.3 Limitations

According to practical applications in different environments, the robot has some limitations (Niku, 2001 & Bekey, 2005).

- Assembly dexterity does not match that of human beings, particularly where eye-hand coordination required.
- Robot structural configurations often constrain joint limits and thus the work volume.
- Work volumes can be constrained even further when parts of substantial size are picked up or when tooling/sensors added to the robot.
- The robot repeatability and/or accuracy can constrain the range of potential applications.

2.2.4 Nomenclature of robot

a) Kinematics

The kinematics deals with the geometry of motion of a body or system of bodies, without consideration of the forces involved (Asada, 2005). It describes the spatial position of bodies or systems, their velocities, and their acceleration. However, the kinematics is described in simple words that it is motion around the environment (Ghoshal, 2009). The kinematics of an arm is normally split into forward and inverse solutions.

b) Dynamics

It is the study of forces and their effects on motion (Saha, 2008). The dynamics of a robot arm are very complicated as they result from the kinematical behavior of all masses within the arm's structure. It is computation of forces and torques required for the execution of typical motions provides useful information for transmissions and actuators (Sciavicco *et al*., 2010).

c) Maneuverability

The word maneuver means an act or instance of changing the direction of a moving vehicle or object (Haji *et al*, 2010). In case of automobile, vehicle maneuverability and stability are defined as a kind of capacities that in the condition of the driver does not feel any nervous and fatigue. The vehicle can be set the direction of traffic by the driver through the steering system and steering wheel, and when encountered outside interference, the vehicle can resist the interference to maintain the stability of travelling.

d) Tele operated

Tele operated robots are controlled by human guidance with remote control device. The remote control signals can be sent through a wire and also through a local wireless system i.e. Blue tooth and Wi-Fi (Espinosa *et al*., 2010).

e) Servo-Controlled Robot

The control of robot, through the use of a closed loop Servo-system in which the position of the robot axis is measured by feedback devices and is stored in the controller's memory. According to Johns (2007) Servo is ideal for applications requiring absolute positioning of a motor shaft.

f) Servo Motor

An electrical power mechanism used to affect motion, or maintains position of the robot. Servo can be DC motor with a built in controller (Johns, 2007). The motor responds to a signal received from the control system and often incorporates an encoder to provide feedback to the control loop.

g) Servo-System

A system in which the controller issues commands to the motors, the motors drive the arm, and an encoder sensor measures the motor rotary motions and signals the amount of the motion back to the controller. This process is continued many times per second until the arm is repositioned to the point requested (Johns, 2007).

h) Stepper motor

Stepper motors are incremental motors powered by electrical pulses or steps (Tang, 2002). The shaft or spindle of a stepper motor rotates in discrete step increments when electrical command pulses are applied to it in the propeller sequence (Saha, 2011). One of the most significant advantages of a stepper motor is its ability to be accurately controlled in an open loop system.

i) Controller

An information processing device, whose inputs are received from computers and controlling motor or actuator motion, coordinates the motions with the sensory feedback information (Niku, 2001).

2.3 Mobile robot

The mobile robot system consists of many subsystems or components to complete the functionalbilty of robot. These subsystems/components are interlinked together and work reatively. The ability to cross the high obstacles and large gaps, the mobile robot should be in flexible and versatile locomotion mechanism. In most cases the working place is complicated, which includes high obstacles, steps, rough surface, narrow fences and debris floors. As the result, the robot should be capable to achieve and complete the various tasks in complex environments (Zhang *et al*., 2006). In order to enhance the work ability of robots, it becomes necessary to consider efficient locomotion mechanism, mainly for outdoor applications (Adachi & Koyachi, 2001). The hybrid locomotion mechanism seemed effective and efficient in all type of environments as compared to individual locomotion mechanism (Lacagnina *et al*., 2003). The use of many locomotion modes would results an appropriate motion mechanism of robot for the persisting conditions in the work environment (Michaud *et al*., 2005). Conceptual, innovation, functional design, performance evaluation and design update are the key processes for the prototype design of mobile robot (Xu *et al*., 2009). Mobile robot's performance, cost of fabrication, development risk and relation to environment must be seriously considered for economic design, see in Figure 2.3.

By the increasing demand of automatic technology, the researchers and scientists had focused their efforts towards development of high level of autonomy and versatile robotic platforms. The robot should be capable to work either individually or with team and possess the structural modular morphology, to adapt the unstructured nature of real environments (Moubarak & Ben-Tzvi, 2011). It is not surprising that high mobility on various environments has been a primary factor among others when evaluating the performance of the mobile robot.

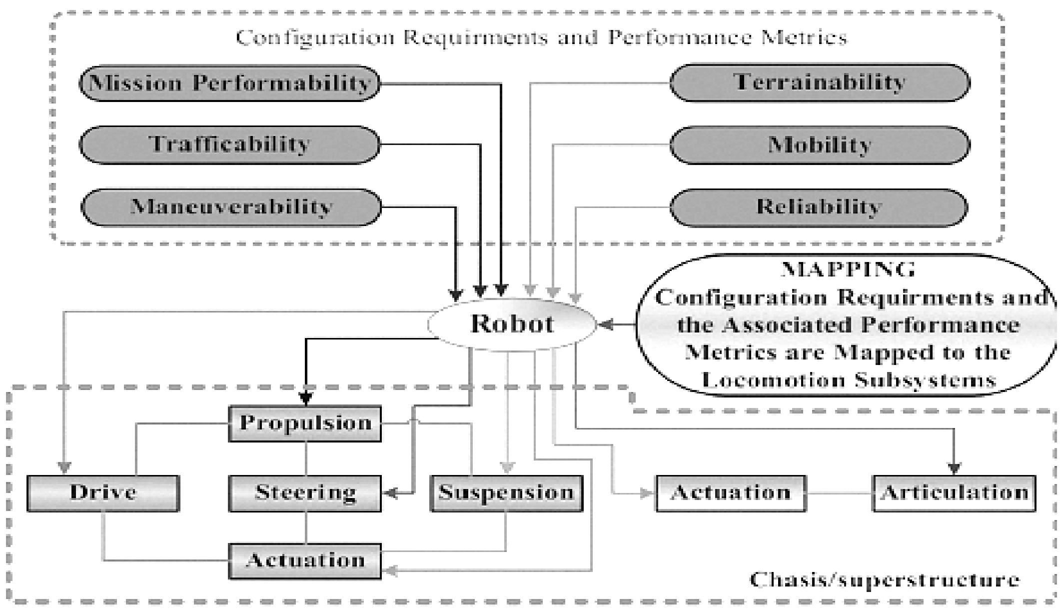

Figure 2. 3 Mobile robot design diagram (Xu *et al*., 2009)

2.3.1 Control

Mobile robots need to constantly process large amounts of sensory data in order to execute required controlled motions based on the manual commands or automatic (Ben Tzvi *et al*., 2008). The control engineering involves the design of an engineering product or system where a requirement is to accurately control some quantity. In principal one can control a quantity in a so called open loop manner where knowledge has been built up on what input will produce the required output. If the feedback is added in the system, to get the system or tool behavior during process is called closed control system.

2.3.2 Mobility

Mobility gives a robot much greater flexibility to perform new, complex and exiting task (Goris, 2005). It is the main feature to be considered while design mobile robot. The mobile robot should be rich in terms of motion abilities, because it deals with very difficult and complex environments to move towards task or goal.

2.3.3 Path Planning

Path-planning is an important characteristic for autonomous mobile robots that lets robots find the shortest or optimal path between two points. The optimal path could be a path that minimizes the amount of turning, the amount of braking or whatever a specific application requires. The path planning for autonomous mobile robot is to search a collision free path (Hachour, 2008). Path-planning requires a map of the environment and the robot to be aware of its location with respect to the map.

2.3.4 Navigation

Navigation system is to guide the robot towards the goal point without a collision with obstacles (Abiyev *et al*., 2010). Robot navigation system includes different interrelated activities such as perception obtaining and interpreting sensory information; exploration the strategy that guides the robot to select the next direction to go; mapping the construction of a spatial representation by using the sensory information perceived; localization the strategy to estimate the robot position within the spatial map; path planning the strategy to find a path towards a goal location being optimal or not; and path execution where motor actions are determined and adapted to environmental changes.

2.4 Mobility system

To achieve a novel technique of locomotion and control mechanism for mobile robots, many researchers, engineers and scientists all over the world have made many attempts and experiments. The use of mobile robots become versatile and it can move freely in multi environments for different applications. According to a locomotive mechanism to achieve the desired mobility, mobile robots may be split into following categories: leg-type, track-type and wheel-type mobile robots (Kim *et al*., 2012). Mobile robot technology has reached to a maturity level at which, it should soon be possible to use rugged, portable mobile robots for various missions that include indoor and outdoor environments. Mobile robots are effective to work in such environments, where to the send the human is not safe, and affordable (Enayati & Najafi, 2011). Mobility system or locomotion system includes three kinds for motion mechanism such as; wheel, track, and leg system (Hasnan *et al*., 2014) as shown in Figure 2.4.

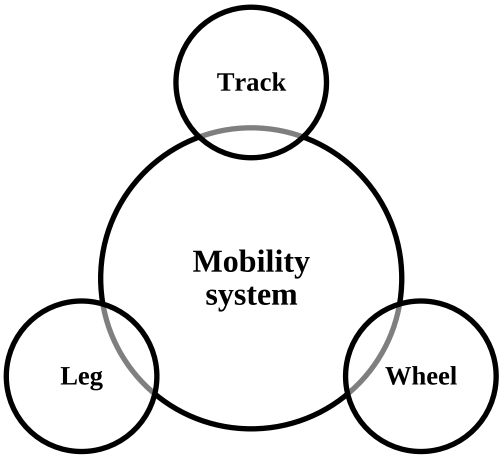

Figure 2. 4 Mobility system (Hasnan *et al*., 2014)

2.4.1 Wheel Type Locomotion

In 2009, Xu *et al*, presents a reconfigurable wheel mobile robot, with multi manoeuvre ability and obstacle avoidance mechanism, shown in Figure 2.5. It has four independent wheels for propulsion and steering system, one wheel at centre of robot for driving force and slip rate. The diverse locomotion modes results the robot with high manoeuvrability, mobility and low energy consumption. In 2010, Li *et al*, proposed a rocker type coal mine rescue robot shown in Figure 2.6, it consist 4 wheels drive with bevel gear mechanism. The rocker suspension provides the stable mechanism for drive in all type of terrains. In 2012, rocker-bogie mechanism was used in robot, which enhanced robots locomotion, abilities and flexibility. The Taguchi method is used as an optimization tool to make the trajectory of center of mass close to the straight line while all wheels keep in contact with the ground during climbing stairs (Kim *et al*., 2012).

In 2012, Ushimi & Aoba, proposed a Two Wheels Caster (TW-Caster) type of odometer for dead reckoning of Omni-Directional Mobile Robots (ODMRs). It is composed of two passive wheels and one passive rotational axis with a dual shaft. An innovative mechanical design approach was introduced by Muniandy & Muthusamy in 2012, to overcome the deficiencies associated with the differential drive kinematic configuration. The working principle of this robot mechanism shows, how the entire drive train formulation guarantees a continuous straight-line motion capability. Lee *et al*., in 2012, presents a novel mechanism and simple locomotion system for pipe inspection, it use a four unit wheel locomotion system. Each unit consist pair of wheel, this type of robot can work with fast speed, low energy consumption and less actuation system. It has high manoeuvrable ability within the pipe according to pipe shape and dimensions.

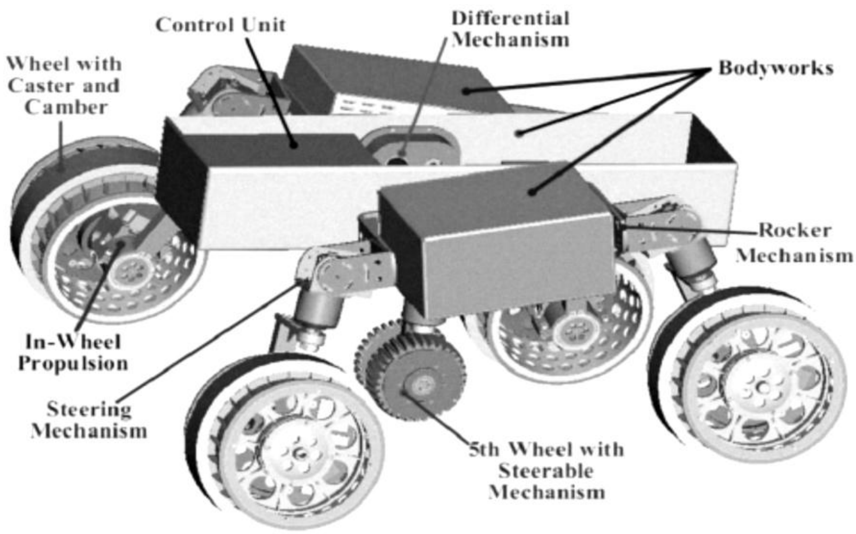

Figure 2. 5 Five wheel mobile robot (Xu *et al*., 2009)

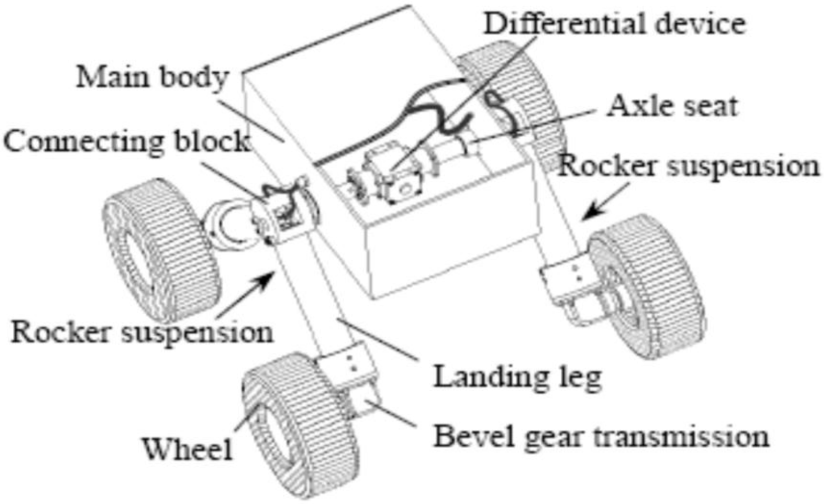

Figure 2. 6 Rocker type four wheel robots (Li *et al*., 2010)

2.4.2 Tracked system

In 2006, Zhang *et al*., presented a shape shifting robot with 3 modules shown in Figure 2.7. The JL-I robot have a large variety of configurations owing to the pose adjusting joints and the docking mechanisms to get best locomotion capabilities. Its serial and parallel mechanisms form an active joint, which enabling it to change the shape in three dimensions. Three degrees of freedom (DOFs) and two tracked drive system proposed by Ye & Lii, in 2006 named as Amoeba-II. It's a shape-shifting mobile robot with two modular mobile units and a joint unit, its locomotion is in tracked mechanism, the joint unit can transform the robot shape for getting high mobility. In 2007, Marques *et al*, presented a tele-operated tether docking system mobile robot named as RAPOSA see Figure 2.8. Its mechanical structure is composed of a main body and a front body, whose locomotion is supported on tracked wheels, allowing motion even when the robot is upside down. The front part (flipper) of the system has excellent tilting abilities, which helps the robot main body to cross the high edges and steps, while climbing the stairs. When only the main body has ground contact, the flipper used to grab the lower ground.

In 2009, Li, B., proposed a shape-shifting mobile robot called AMOEBA-I. It has 3 modules, 2 link arms with 7 DOF, 2 pitch joints and 2 yaw joints. The key advantage of this design over other mobile robots is its adaptability and flexibility because of its various configurations. It can change its configuration fluently and automatically to adapt to different environments or missions. In 2010, Miro & Dissanayake, introduced a mobile robot, which consist track base with two front flippers that enable the robot to traverse obstacles and rough terrain. A manipulator arm unit with cameras, lights and sensor also enhance the Search and Rescue capabilities, victim identification activities. In 2011, Enayati & Najafi, proposed a novel mobility system of a tele-operated mobile robot. This system helps the robot to gain high manoeuvrability on rough terrains. The robot was tested on a standard test arena and the results were compared with another similar type of robot. Although the implemented locomotion mechanism is the common tracked type, adding the centre tracks and arrangement of arms are original ideas which help the robot to gain high manoeuvrability. Vincent & Sun, in 2012 presented a Shape shifting tracked robotic vehicle (STRV) for rescue operation, which can be able to move in all type of obstacles, paths at constant nominal propulsion speed.

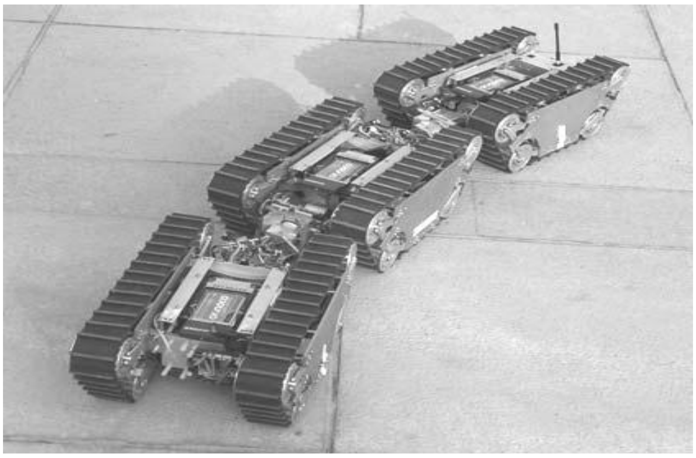

Figure 2. 7 Reconfigurable mobile robot (Zhang *et al*., 2006)

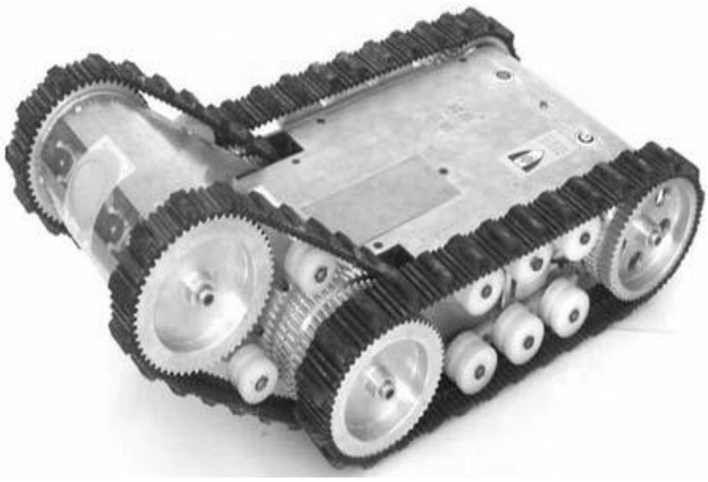

Figure 2. 8 RAPOSA mobile robot (Marques *et al*., 2007)

2.4.3 Legged system

In 2011, Sintov *et al*, proposed a new design of four leg mobile robot, which can climb on wall named as CLIBO shown in Figure 2.9. It uses four limbs to climb and implements the method used by cats to climb on trees utilizing their claws. It has four legs with 4-DOF and specially designed claws attached to each leg. At the tip of each leg is a gripping device made of 12 fishing hooks and aligned in such a way that each hook can move independently on the wall's surface. Vidoni & Gasparetto in 2011, introduced an eight legged spider like robot as shown in Figure 2.10, by considering the anatomy and the adhesive and locomotion capabilities of the spider. They focused on the foot force and torque distribution in different operative, slope conditions and a posture evaluation by comparing different leg configurations in order to minimize the torque effort requirements.

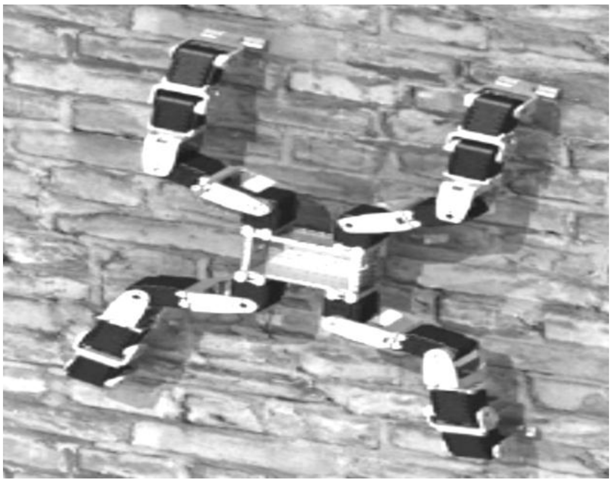

Figure 2. 9 CLIBO mobile robot (Sintov *et al*., 2011)

Figure 2. 10 Eight legged spider like robot (Vidoni & Gasparetto, 2011)

2.4.4 Hybrid system

To enhance the mobility system and flexibility of mobile robots the locomotion mechanism changed by adding two or more systems together, wheel + tracked and wheel + legged etc. In 2009 Bayar *et al,* presented a design of hybrid mechanism mobile robot named as CoMoRAT (Configurable Mobile Robot for All Terrain Applications) shown in Figure 2.11. CoMoRAT can be driven by wheels, tracks or both, besides its ability to ride effectively on various terrains. The test results regarding velocity and power consumption shown in Table 2.1. In 2011, Quaglia *et al*, presented wheeled and legged hybrid locomotion robot, named as Epi.q-TG shown in Figure 2.12. It consist four wheeled locomotion units, each unit equipped with three wheel set. Each front unit is actuated by a single motor with the interposition of an epicyclical gear system, accurately designed in order to interchange between wheeled and legged motion. It changes locomotion mode from rolling on wheels and to stepping on legs, with respect to the local friction and dynamic conditions. The robot behaves like a four-wheeled vehicle in advance mode, with high speed and energy efficient.

Table 2. 1 Velocity and Power consumption (Bayar *et al*., 2009)

		Current drawn during the motion (A)	**Time travelled (Sec)**	**Velocity (m/s)**
Wheeled	Indoor	1.1 – 1.3	16.6	0.8
	Outdoor	1.4 – 2.2	20	0.7
Tracked	Indoor	0.9 – 1.1	12.5	0.6
	Outdoor	1.1 – 1.5	14.5	0.5
Wheeled + Tracked	Indoor	1.3 – 1.4	14.7	0.7
	Outdoor	1.5 – 2.5	17	0.6

Mahboubi *et al,* in 2013, proposed a novel hybrid spherical mobile robot; the slipping is one of the most important problems of their motions. To overcome this problem, a hybrid structure of the spherical mobile robots and ordinary quadruped robots introduced. By adding four legs to the spherical mobile robot, better results were obtained than ordinary spherical robots. Using the feet can reduce slip and increase the stability of the spherical robots. Experimental results expressed that it is more stable in motion in comparison with the other types of spherical mobile robots.

In 2012, Roslin *et al*, proposed a hybrid system used for pipe inspection. It is based on wheeled type, caterpillar type, snake type, legged type, inchworm type, screw type and PIG type. The combination of two or more locomotion system had been implemented to pipe inspection robot for more advantages in terms of robustness and flexibility. By using hybrid locomotion system, the inspection robot was able to adapt and navigate in a various pipe configuration.

Figure 2. 11 CoMoRAT Hybrid robot (Bayar *et al*., 2009)

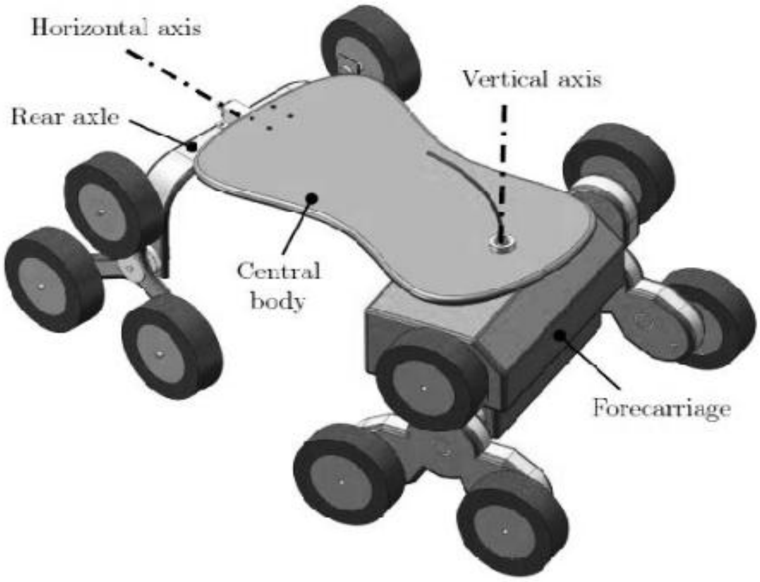

Figure 2. 12 Epi.q-TG Hybrid robot (Quaglia *et al*., 2011)

2.4.5 The development of single locomotion system mobile robot

There are two type of locomotion system mainly focused for research within mobile robots. One is to research or develop robot with one locomotion mechanism like wheeled robot, tracked type robot or legged based robot. The other is to build combined locomotion mechanism named as hybrid system, in which more than one mechanism designed together. A summary of current development in mobile robots and their characteristics is illustrated in Table 2. 2.

Table 2. 2 Summary of single locomotion mobile robot (2006 - 2012)

First author and Model name	Year	Locomotion type	Features
Zhang (JL-1)	2006	Track	A shape shifting robot with 3 modules. The JL-I robot have a large variety of configurations owing to the pose adjusting joints and the docking mechanisms.
Marques (RAPOSA)	2007	Track	RAPOSA designed with two units, main body and front flippers. The flippers help the robot to climb into stairs and high obstacles. It consists of camera, temperature and humidity sensors.
Molfino	2008	Crawl	Its mechanism is like snake and worm, using the principal of continuous sliding membrane to achieve effective propulsion ratio.
Li (Amoeba -1)	2009	Track	It has 3 modules, 2 link arms with 7 DOF, 2 pitch joints and 2 yaw joints. It can work on land surface and in water. It has ability to change the shape according to path and terrain.
Yunwang	2010	Wheel	It is a rocker type coal mine rescue robot consist 4 wheels drive with bevel gear mechanism. The rocker suspension provides the stable mechanism for drive in all type of terrains.
Miro (Packbot)	2010	Track	It consists of track base with two front flippers that enable the robot to traverse obstacles and rough terrain. A manipulator arm unit with cameras, lights and sensor to enhance the Search and Rescue capabilities, victim identification activities
JiPing	2010	Crawl	Robot made of a flexible material, which can adopt the shape according to the path or environment. Locomotion is similar to amoeba with ionic polymer metal composite (IPMC) actuator.
Zhou	2011	Track	Double track system on both side of base unit. To avoid the slipping of robot move on various terrains by using back stepping method combined with scaling technique.
Sintov (CLIBO)	2011	Legged	A four leg robot capable of climbing on vertical and rough surfaces, with 4-DOF and specially designed claws attached to each leg. At the tip of each leg is a gripping device made of 12 fishing hooks and aligned in such a way that each hook can move independently on the wall's surface.
Richardson	2011	Crawl	Small rescue robot with 2 side arms. The force applied by arms on contacting surface, which cause the robot body moves. The arms consists 4 bar links, work in quick return mechanism.
Enayati	2011	Track	A novel track arrangement with additional mechanisms in mobile robot, which help the robot to gain better maneuverability on rough terrains. A new rear arm mechanism is introduced in the robot.
Vincent (STRV)	2012	Track	Shape shifting tracked robotic vehicle (STRV) for rescue operation, which can be able to move in all type of obstacles, paths at constant nominal propulsion speed.
Kim	2012	Wheel	Rocker-bogie mechanism used in this robot, which enhance its locomotion abilities and flexibility. The Taguchi method is used as an optimization tool to make the trajectory of centre of mass close to the straight line while all wheels keep in contact with the ground during climbing stairs.

The comparison between the mobility systems was done by the data taken from the current study given in Table 2.2. The use of each system in percentage is shown in Figure 2.13; it gives the relative comparison between track, wheel, crawl and legged system.

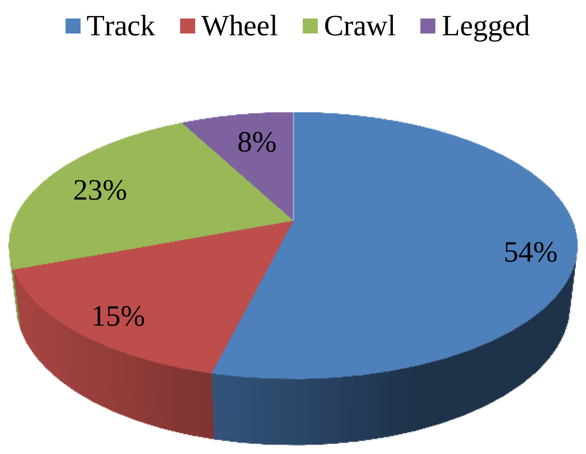

Figure 2. 13 Comparative study for individual locomotion

The mobility system data are shown in Figure 2.14; it gives a clear result about the type of locomotion used since last few years. From our study, it is concluded that the track system used 54%, Crawl 23%, wheel 15% and legged 8%. Wheel mechanism is the most popular drive mechanism of mobile robots. It is compact and easy to use but it is difficult to adapt the uneven and complicated environments. Such types of robots are also more likely to fall down or slip on the inclined and uneven pathway. These types of robots are good in structured environments.

Track mechanism enables mobile robots to work in the unstructured areas shaped by natural disasters. Because of advantages such as excellent stability and low terrain pressure and more researchers take interest in tracked mobile robot which can move in unstructured environment quickly and the development of tracked robots with different functions has been carried out extensively. However, it is not competent for track type robot to climb in vertical obstacles or walls.

The legged type mobile robots are more feasible to all type of environments. They have advantageous at walking on the uneven rubble surface but its mechanism is quite complicated because of active control equipped are required with additional actuators and sensors for maintain the balance, which cause to slow movement and poor energy efficiency.

The snake type or crawl type robot are very good in flat surface because of their twisting or zigzag movement. These robots are unable to climb or move through steps, mud, sedge or scrubby terrains.

2.4.6 The development on hybrid locomotion system

To enhance the mobility system and flexibility of mobile robots the locomotion mechanism changed by adding two or more systems together such as wheel and tracked, tracked and legged, wheel and legged as illustrated in Table 2.3. The hybrid systems are more effective and efficient as compared to the individual mobility systems in locomotion. But there control in terms of maneuverability from one system to another is difficult. There are many possible ways, which makes the selection of a robot's approach to effective locomotion system for their design shown in Figure 2.14. Most of these locomotion mechanisms have been inspired by their biological counterparts, which are adapted to different environments and tasks.

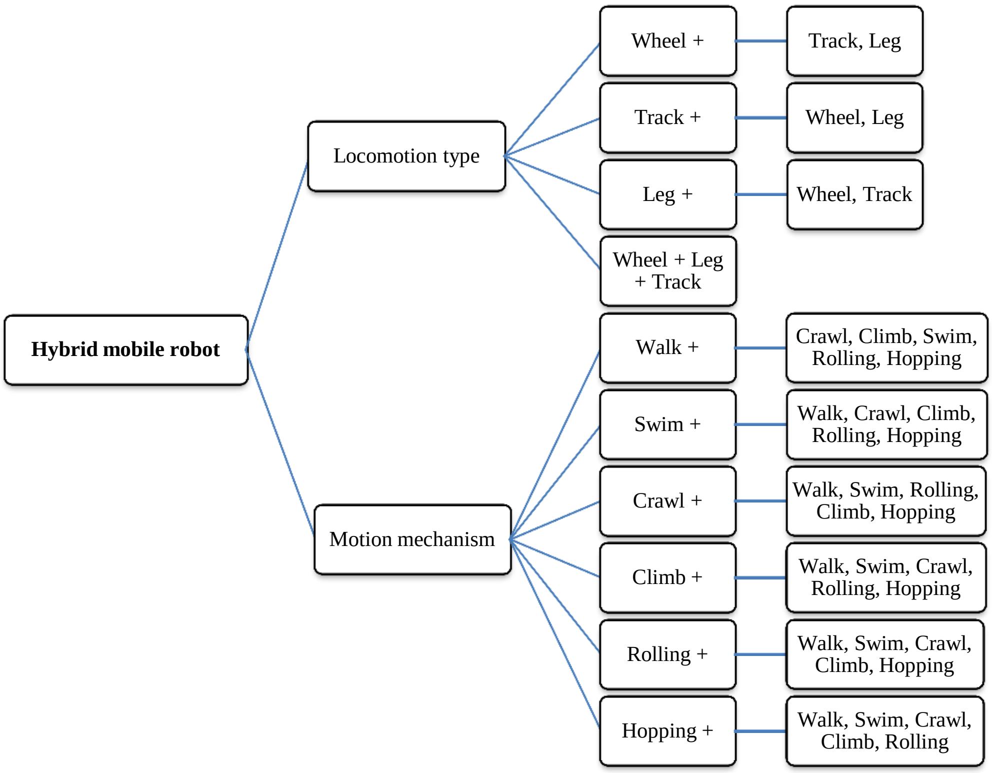

Figure 2. 14 Possible hybrid locomotion systems for mobile robot

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