Design, Simulation and Analysis of Self-Reconfigurable Robot

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***Abstract*—This paper presents a hybrid robot that achieves locomotion through legs and wheels. The fixed mobile robots not become accustomed themselves to the environmental changes. To overcome this, the self reconfiguring robots are able to purposely modify their individual shape by rearranging the connectivity of their parts to meet particular operational demands. Recently, there has been a great concern in using self-reconfigurable robots in applications such as space exploration and rescue missions. Designing and controlling of self-reconfigurable robots is a difficult task. Hence, the research has mostly been focused on emergent systems that can function in a controlled environment. The future work of this paper is to develop the robot with various modes to navigate in any terrain.**

***Keywords*—Mobile robots; hybrid robots; self-reconfigurable robots; kinematics; robotics simulation**

I. INTRODUCTION

Reconfiguring robots will be most suitable for human environment with greater effectiveness than any other type of robot. It is hoped that eventually reconfiguring robots can be used to perform tasks which are difficult, dirty and dangerous (3D) for humans. This design is intended to operate in an uneven and unbalanced environment with the facility of sensing and communicating with other modules [2]. This includes working in extreme environmental conditions or as an aide to humans in similar situations. The fixed mobile robots not turn out to be used to the morphological changes. Morphogenetic is the approach of multi cellular organisms inspired by the emergent improvement [24]. These types of robots are well-suited for locomotion in strange environments.

There are varieties of locomotion mechanisms to move and hence robot's locomotion approach plays a vital role in mobile robot design. Some of them are walk, run, fly, slide and skate etc [8]. Generally the mobile robots can locomote either through wheels or by leg. Self repairing, self sustaining, self replication and self extension are some of the challenges mentioned in these methods [16].

Biological systems succeed in moving through a variety of different environments. Therefore, it can be advantageous to replicate their choice of locomotion mechanisms.

Recently, there has been a noteworthy progression in the field of reconfiguring robots. A variety of robots that are designed to operate in environments populated by humans has already been developed [21]. The Robot is developed especially to move in any terrain i.e. both walk using legs and move on wheels. The modular and reconfigurable mobile robots in environments that is hazardous and unapproachable to humans [18]. These robots are able to operate as a swarm and provide higher versatility [4]. They have also categorized the reconfigurable robots based on structural properties as Mobile Configuration Change and Whole Body Locomotion [17]. The speed achieved is same when the robot walks on smooth as well as rough terrains [7]. The robot can navigate using wheels on both flat and rugged terrains. The performance of the motor can be utilized by the introduction of motor driver which always provide maximum output current than input current of the motor [11].

Each robot's mission is to reach the destination even in unstructured terrains and avoiding collision with the other robots [4]. The self reconfiguration robot should be aware of their environment and their own circumstances through a sequence of sensors [3]. The fusion of information from various sensors is a tedious process for autonomous decision making [1]. The operations stated are to be achieved by using minimum number of actuators, thereby decreasing the mechanical complexity, programming complexity and cost [22]. So this project is undertaken to make use of the property of transforming on its own with help of various sensor that could make it possible to help in the field of space exploration, rescue missions etc, where human faces a fatal damage [9].

Based on the analysis and study, the interaction of the robot with the environment and robot locomotion plays a vital role in the selection of simulation [6]. The secondary criteria are close to reality, open source and usage of same code for simulation and real robot. V-Rep is an Integrated Development Environment and supports multiple physics engine (ODE, Bullet and Vortex) [20]. The simulation results have confirmed that the proposed method can effectively direct the robot to change their locomotion [5].

II. QUADRUPED ROBOT

The proposed approach implements a wheeled quadruped robot. There are various design considerations when designing the robot. Self Reconfiguring robots require unique controller and actuator for each module and then the modules are integrated [18]. The locomotion of robots has been extensively analyzed and studied. From those studies and surveys, a quadruped robot with mammalian gait pattern with static stability is planned to design and certain transformations are employed to make it work like a versatile reconfigurable robot [13]. At least three feet should be placed on the ground to achieve the static stability and maintaining the center of gravity within the support polygon.

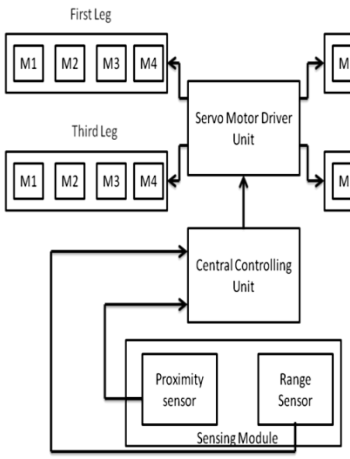

Fig. 1. Block Diagram of the proposed Robot.

The block diagram of the proposed self reconfiguring robot is shown in the figure 1. The power is supplied through battery to various components. These components are controller board, driver circuit board, sensor modules and motors. The obstacle and variation in the environment is sensed through sensing modules and send to the controller for the decision making. The data are processed by the controller and the required signals are sent to the motors through the driver board. The sensing modules continuously monitor the environment for any change.

A. Conceptual Design

Primarily the reconfiguring robot was conceived with sixteen degrees of freedom with four degrees of freedom per leg (Fig 4). Due to difficulties faced in controlling greater number degrees of freedom, this robot is redesigned with three degrees of freedom per leg so as to have twelve degrees of freedom. Lastly, a new design was arrived with the knowledge gathered from developing previous models. The new design has got twelve degrees of freedom with three degrees of freedom per leg (Fig. 1). This design has more stability with equal weight distribution on all the legs.

B. CAD Model for Proposed Robot

The joints of the legged robots have to operate in a particular fashion as this is discrete systems [13]. The challenge of mobile robots is achieving controlled locomotion in rough terrains. Walking robot may be a plausible solution to the problem [12]. But this makes the robot motion slow. On a flat terrain there is no need of legs for locomotion because wheeled motion is very much suitable for fast and less power consuming navigation. Thus, wheeled robots are very energy efficient on hard surface even at high speed.

In first design, 4 servo motors are used in each leg with DPST micro switch. The contact between the foot of the robot and surface of the ground can be estimated for the control system of the robot. The model consists of a rectangular frame with 4 servo motors on each leg. These motors are connected with the frame through links. All legs are identical with servo motors are placed as frame motor, Hip motor, Knee motor and ankle motor [11]. The leg is allowed to swing only when the neighboring legs perceive ground contact.

The robot can be modeled by using rectangular frame, links, motors and wheels. The battery which supply power to the motor is placed to the slots provided in the mechanical setup. This is the prototype model created using catia in order to work out what could be the ultimate shape of the robot. The robot has to be planned by considering the following parameters such as wheel diameter, motor dimensions of servo motor and DC motors.

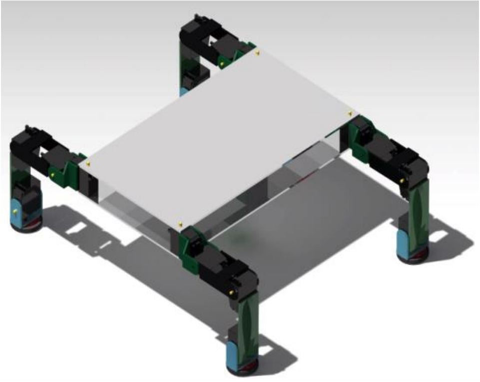

Fig. 2. Proposed CAD Model – Leg Configuration.

The wheel configuration can be initiated by getting feedback from the sensors and achieved by controlling the servo motor. The wheel configuration is suitable for flat and smooth surfaces.

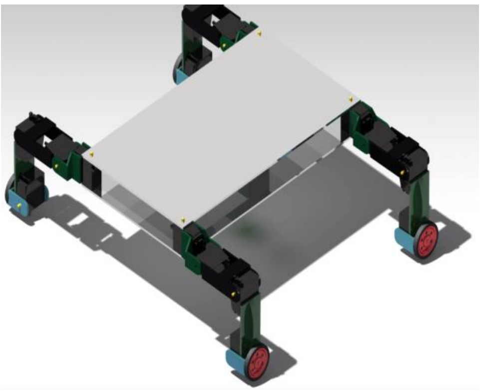

Fig. 3. Proposed CAD Model – Wheel Configuration.

In second design, the number of actuators is reduced to build the robot simpler [19]. In this project, 2 types of U-shaped bracket is used for joints formation. The servo motor holder consists of two parts namely Servomotor bracket i and ii (Fig. 2). Servomotor can be fitted into the bracket i using the provision given in the bracket and the bracket ii can be used to pass on the output of the servomotor. Bracket i and ii are coupled using servomotor horn on one side. By using the brackets there is a greater elasticity and other joints cannot be disturbed while actuating the individual joint. The design of the servo motor holders and brackets are based on the selection of the motor. The dimensions of bracket i and bracket ii are 32x40x75mm and 60x40x50mm respectively.

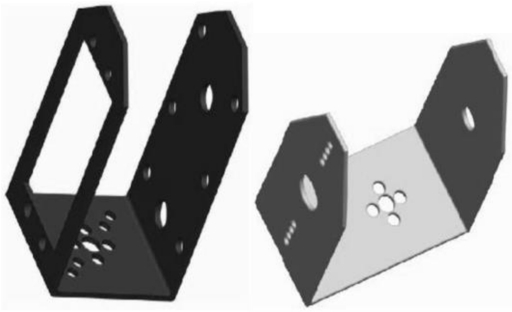

Fig. 4. CAD Model of Servo Motor Brackets.

Each part of the robot body is designed by part designing tools in CATIA and the parts are assembled to form the body structure by using the assembling tool. The parts of the body are Chassis, Servo motor frame (brackets) and leg (limb). Initially the components sizes were analyzed and the optimum size for the robot was determined. Robot size plays a major role. Based on the size of the robot, the Cost of the Project and requirement of the actuators can be determined. The Fig. 6 shows the second design with reduced number of servo motors and simpler mechanical design than the previous versions.

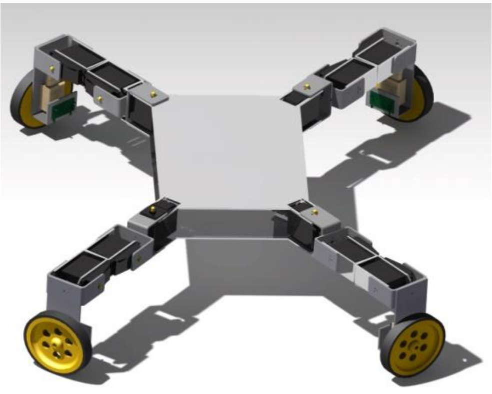

Fig. 5. Proposed New design CAD Model.

C. Kinematics of the Robot

In this work, a four-legged and wheeled robot is developed especially to navigate in any kind of terrains i.e. both walk using legs and move on wheels [13]. The controller will send the required position and orientation of the motor for each leg and robot body by using the kinematic model [23]. The main role of these processors is to convert the desired joint angle values for the joint positions into accurate motor control pulses. The knee of each leg was designed with a DC motor with the wheel.

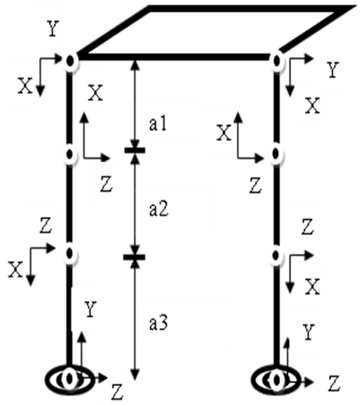

Fig. 6. Co-Ordinate Diagrams for the Front Legs.

The D-H method allows four basic transformations lead to a unique homogeneous transformation matrix ${}_{i}L_{i-1}$ with four variables representing the relationship between the links which is given by the equations.

$${}_{i}L_{i-1} = [rot\,(z, \theta_{i-1})\ tran(0, 0, d_{i-1})\ tran(a_{i-1}, 0, 0)\ rot(x, \alpha_{i-1})] \quad (1)$$

$${}_{i}L_{i-1} = \begin{bmatrix} \cos\theta_i & -\cos\alpha_i \sin\theta_i & -\sin\alpha_i \sin\theta_i & a\cos\theta_i \\ \sin\theta_i & \cos\alpha_i \cos\theta_i & \sin\alpha_i \cos\theta_i & \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

The DH convention of a 4-DOF robotic leg and correspondingly the transformation matrices are computed by using the above equations for the joints and these can be explained by the following table.

TABLE 4.1 DH CONVENTION OF 4-DOF ROBOTIC LEG

Joint	θ_i	α_i	a_i	d_i
1	Θ_1	-90°	0	0
2	Θ_2	90°	a1	0
3	Θ_3	0°	a2	0
4	Θ_4	0°	a3	0

The transformation matrix from foot to hip is the concatenated transformation from link-to-link. Because both legs have the same mathematical representation, only one matrix had to be calculated for both legs. This matrix, considers as a base coordinate system, the origin of the hip servos axis of each leg. By homogeneous transformation, the position and orientation of the base frame will be given by the equations,

$${}_{0}L_{1} = \begin{bmatrix} \cos\theta_1 & 0 & \sin\theta_1 & 0 \\ \sin\theta_1 & 0 & -\cos\theta_1 & \sin\theta_1 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$ {}_{1}L_{2} = \begin{bmatrix} \cos\theta_2 & 0 & \sin\theta_2 & a_1\cos\theta_2 \\ \sin\theta_2 & 0 & -\cos\theta_2 & \sin\theta_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4) $$

$$ {}_{2}L_{3} = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & a_2\cos\theta_3 \\ \sin\theta_3 & \cos\theta_3 & 0 & \sin\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5) $$

$$ {}_{3}L_{4} = \begin{bmatrix} \cos\theta_4 & -\sin\theta_4 & 0 & a_3\cos\theta_4 \\ \sin\theta_4 & \cos\theta_4 & 0 & \sin\theta_4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6) $$

The matrices are multiplied to get ${}_{0}T_{4}$ and then the following link length given in the equations are submitted,

$$ a = [0\ 0.40\ 0.52\ 1.2] \quad (7) $$

The total transformation between the body of the robot and foot of the robot leg is

$$ {}_{0}T_{4} = {}_{0}L_{1}.{}_{1}L_{2}.{}_{2}L_{3}.{}_{3}L_{4} \quad (8) $$

$$ = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (9) $$

WHERE,

$$ n_x = c\theta_1 c\theta_2(c\theta_3 c\theta_4 - s\theta_3 s\theta_4) + s\theta_1(-s\theta_3 c\theta_4 + c\theta_3 s\theta_4) \quad (10) $$

$$ o_x = c\theta_1 c\theta_2(-c\theta_3 s\theta_4 - s\theta_3 c\theta_4) + s\theta_1(-s\theta_3 s\theta_4 c\theta_3 c\theta_4) \quad (11) $$

$$ a_x = c\theta_1 s\theta_2 \quad (12) $$

$$ p_x = c\theta_1 c\theta_2(a_3 c\theta_3 c\theta_4 - s\theta_3 s\theta_4 + a_2 c\theta_3) + s\theta_1(a_3 s\theta_3 c\theta_4 + c\theta_3 s\theta_4 + s\theta_3) + a_1 c\theta_1 c\theta_2 \quad (13) $$

$$ n_y = s\theta_1 c\theta_2(c\theta_3 c\theta_4 - s\theta_3 s\theta_4) - c\theta_2(-s\theta_3 c\theta_4 + c\theta_3 s\theta_4) \quad (14) $$

$$ o_y = s\theta_1 c\theta_2(-c\theta_3 s\theta_4 - s\theta_3 c\theta_4) - c\theta_2(-s\theta_3 s\theta_4 + c\theta_3 c\theta_4) \quad (15) $$

$$ a_y = s\theta_1 s\theta_2 \quad (16) $$

$$ p_y = s\theta_1 c\theta_2(a_3 c\theta_3 c\theta_4 - s\theta_3 s\theta_4 + a_2 c\theta_3) - c\theta_2(a_3 s\theta_3 c\theta_4 + c\theta_3 s\theta_4 + s\theta_3) + a_1 c\theta_1 c\theta_2 \quad (17) $$

$$ n_z = -s\theta_2(c\theta_3 c\theta_4 - s\theta_3 s\theta_4) \quad (18) $$

$$ o_z = -s\theta_2(-c\theta_3 s\theta_4 - s\theta_3 c\theta_4) \quad (19) $$

$$ a_z = -c\theta_2 \quad (20) $$

$$ p_z = -s\theta_2(a_3 c\theta_3 c\theta_4 - s\theta_3 s\theta_4 + a_2 c\theta_3) - s\theta_2 \quad (21) $$

The above equations are solved to give certain angles that can be employed for pure rotation of motors while reconfiguring of the robotic parts. The analog servo motors have an integrated potentiometer in the position control mode to enable the closing of the feedback loop. Each servo motor has to be manually calibrated to avoid the errors in position control.

III. SIMULATION MODEL

Simulation software is a tool for testing behaviors before trying them on the real robot. After the kinematic analysis is done, the V-Rep simulator is used to simulate the robot in an integrated development environment. Robot walk can be evaluated by stability, velocity attained and torque required at each joints.

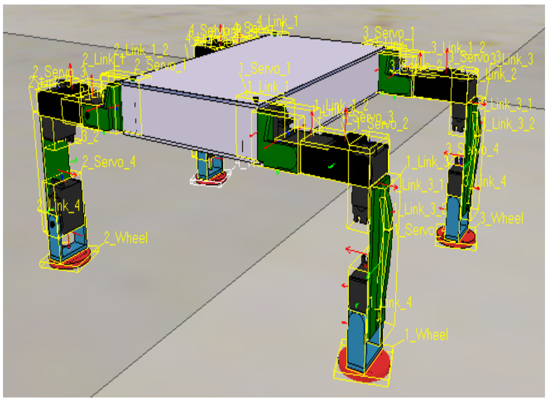

Fig. 7. Inverse Kinematics in V-REP Simulator.

The gait pattern of this robot is determined prior to the design and fabrication of the model. The developed model is simulated for statically stable amble gait. The Fig. 8 shows the demonstration of the robot in leg mode using Virtual Robot Experimentation Platform simulator environment.

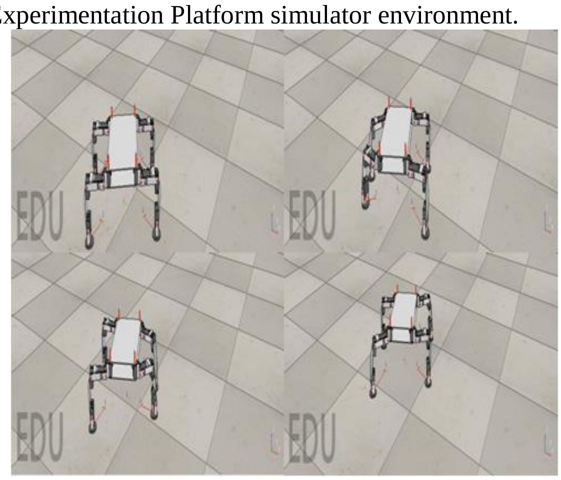

Fig. 8. Leg mode GAIT Pattern in V-Rep.

The wheel mode can be obtained whenever the controller receives more values from the proximity sensor than the reference values. The Fig. 9 shows the switching between leg mode and wheel mode. The hybrid structure is used to optimize the performance in terms of speed and stability when the robot takes different kinds of transformations [15].

Wheels act as foot while walking motion and do rolling motion in wheel mode.

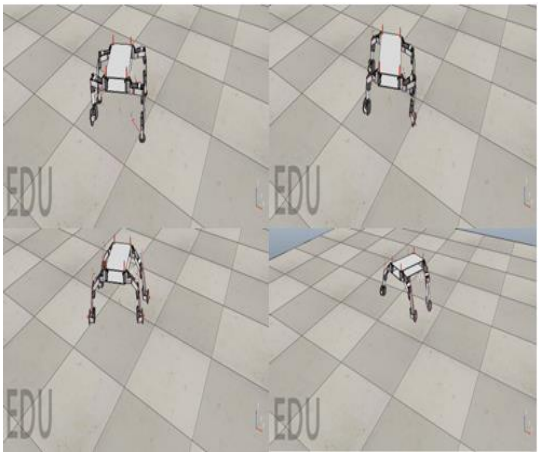

Fig. 9. Wheel mode GAIT Pattern in V-Rep.

Simulations are carried out for different configurations and the assumptions for the analysis are robots walk in amble gait pattern only. This can be shown in the Fig. 10. Similarly, the requirement of the torque at each joint for the actuators can be determined from the Fig. 11.

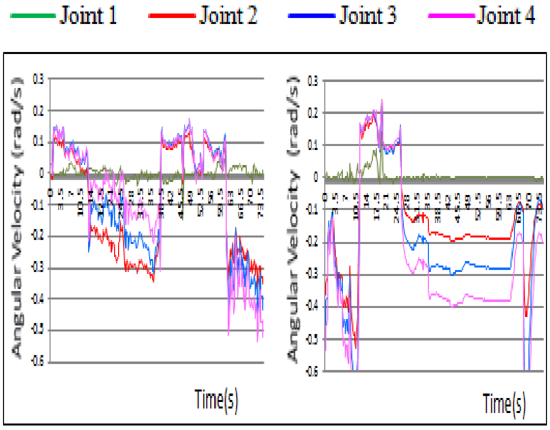

Fig. 10. Angular Velocity (rad/s) vs Time(s).

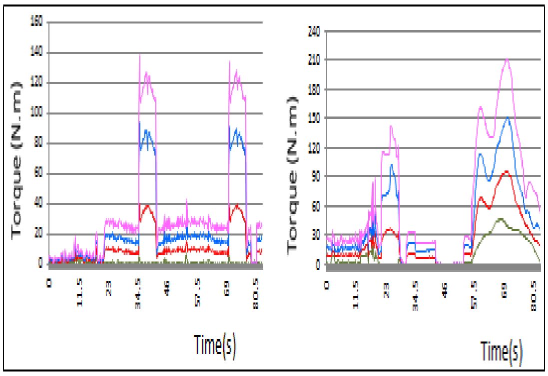

Fig. 11. Torque (Nm) vs Time (s).

There will always be a difference between simulation and reality and hence the gap should be taken into account. As this simulator software supports script language for programming, there is a need for the change of programming language in a real environment.

IV. CONCLUSION

An extensive Literature Survey conducted for the work gave profound insight on the requirements for building the robot. Based on the inferences obtained from the survey, the further development for the paper was carried out. CAD model has been created and analyzed using virtual robot experimentation platform. The angles obtained from the D-H matrix can be used to give inputs to the servomotor. These can be analyzed by the corresponding torques at various times for the joints during simulation. The robot's locomotion can be obtained by placing three legs on the ground thus follows stable amble gait. The angular velocity for each joint can be recorded over the period of time.

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