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Implementation of Reconfigurable Robot Mechanism for Earthquake Rescue Operation

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ABSTRACT

Demands for Multi Terrain robot application have been increased significantly in the past few decades. These robots have been employed for the purpose of security surveillance and rescue purposes in the remote areas. In remote areas the terrain can't be determined and hence stability of the robot becomes a challenging task if it's not uniform. Hence, in this project, a new reconfigurable mechanism consisting of drone and land robot will be developed to perform monitoring task while running on different terrains. Drone gets reconfigured to rover to lift it up for a shorter time depending upon the environment it traverses. The entire mechanism is developed for community services. Further, this research work presents the study of shape reconfigurablemechanism of an earthquake rescue robot. The robot based on theshape reconfigurable mechanism is designed to be able tointelligently alter its body shape.

Keywords: Earthquake rescue robot, Shape reconfigurable, Multi terrain, Monitoring task, Roll, Pitch, Orientation, Rover-terrain interaction.

1. INTRODUCTION

Earthquakes are unfortunately frequent happenings and very dangerous natural phenomena. In almost every major earthquake many victims are buried under collapsed buildings, bridges, roadways, etc. It is very difficult to rescue these people, who may well be injured, hungry and weak. In addition, the structural conditions under the rubble can be complex, dangerous and unknown. So, there is a primary need to explore these conditions and determine the victim's location and their condition. As a result rescue robots have been designed for working on the rugged surface [1]. These rescue robots do not show the ability that they can negotiate with variable voids underneath and travel along the void to reach victims buried in the rubbles. Self-reconfigurable robots [2] are constructed of robotic modules that can be connected in many different ways. These modules move in relationship to each other, which allow the robot to reconfigure into each other depending upon the functionality. Articulated all-terrain rovers [3-4] are a class of mobile robots that have sophisticated mobility systems for enabling their traversal over uneven terrain. These robots are being used increasingly in such diverse applications as planetary explorations [5], rescue operations, mine detection and demining, agriculture, military missions [6-7], inspection [8], and clean-up operations of hazardous waste storage sites, remote ordinance neutralization, search and recovery, security, and fire fighting. This research can be roughly divided into two areas - one related to high-level tasks, such as path planning [9], and the other concerning lower level tasks, such as navigation and motion control [10], which require kinematics modelling and analysis of the robot [11]. The kinematics modelling of these robots can be classified into two main approaches, geometric and transformation. The geometric approach is intuitive, but restrictive if used on its own.The transformation approach is widely employed by researchers and

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consists of a series of transformations and their derivatives to relate the motion of the wheels to the motion of the robot. A quadcopter is a popular form of UAV (Unmanned aerial vehicle) [12]. It is operated by using four rotors which are directed upwards and they are placed in square formation with equal distance from the centre of mass of the quadcopter. The quadcopter is controlled by adjusting the angular velocities of the rotors which are spun by electric motors [13]. The thrust from the rotors plays a key role in manoeuvring and keeping the copter airborne. Its small size and swift manoeuvrability enables the user to perform flying routines that include complex aerial manoeuvres. But for conducting such manoeuvres, precise angle handling of the copter is required. The precise handling is fundamental to flying by following a user-defined complex trajectory-based path and also while performing any type of missions [14-16].Quadcopters are used in surveillance, search and rescue, construction inspections and several other applications. Surveying of people is done by using camera attached to the quadcopter manoeuvring at a fixed height from the ground [17]. Ethical issues related to quadcopters deployed in recreational, civilian/commercial and military arenas don’t come into picture because this machine will be used only for the rescue operation when a disaster is happened [18].This paper follows the line of previous work starting from the selection of design to the fabrication process [19-20]. The focus is on simple models so that it allows modelling and simulation with little processing power.

2. BACKGROUND WORK

List of Reconfigurable Robotsand Electrical and Mechanical characteristics of Self-Reconfigurable Robotsare shown in Table I and Table II.

Table 1
List of Reconfigurable Robots[21].

System	*Class*	*DOF*	*Shape*	*Author*	*Year*
Self replicator (SR)	Mobile	-	-	John Von Neumann	1950
Mechanical SR	Mobile	-	-	Lionel Penrose	1959
CEBOT	Mobile	various	-	Fukuda et al. (Tsukuba)	1988
Polypod	chain	2	3D	Yim (Stanford)	1993
Metamorphic	lattice	6	2D	Chirikjian (Caltech)	1993
Fracta	lattice	3	2D	Murata (MEL)	1994
Fractal Robots	lattice	3	3D	Michael(UK)	1995
Tetrobot	chain	1	3D	Hamline et al. (RPI)	1996
ANAT Robot	Chain/tree	-	3D	Charles Khairallah (CA)	1997
3D Fracta	lattice	6	3D	Murata et al. (MEL)	1998
Molecule	lattice	4	3D	Kotay&Rus (Dartmouth)	1998
CONRO	chain	2	3D	Will &Shen (USC/ISI)	1998
PolyBot	chain	1	3D	Yim et al. (PARC)	1998
TeleCube	lattice	6	3D	Suh et al., (PARC)	1998
Vertical	lattice	-	2D	Hosakawa et al., (Riken)	1998
Crystalline	lattice	4	2D	Vona&Rus, (Dartmouth)	1999
I-Cube	lattice	-	3D	Unsal, (CMU)	1999
M-TRAN I	hybrid	2	3D	Murata et al.(AIST)	1999
Pneumatic	lattice	-	2D	Inou et al., (TiTech)	2002

(*contd...*)

(*Table 1 contd...*)

System	*Class*	*DOF*	*Shape*	*Author*	*Year*
Uni Rover	mobile	2	2D	Hirose et al., (TiTech)	2002
M-TRAN II	hybrid	2	3D	Murata et al., (AIST)	2002
Atron	lattice	1	3D	Stoy et al., (U.S Denmark)	2003
S-bot	mobile	3	2D	Mondada et al., (EPFL)	2003
Stochastic	lattice	0	3D	White, Kopanski, Lipson (Cornell)	2004
Superbot	hybrid	3	3D	Shen et al., (USC/ISI)	2004
Y1 Modules	Chain	1	3D	Gonzalez-Gomez et al., (UAM)	2004
M-TRAN III	hybrid	2	3D	Kurokawa et al., (AIST)	2005
AMOEBA-I	Mobile	7	3D	Liu JG et al., (SIA)	2005
Catom	lattice	0	2D	Goldstein et al., (CMU)	2005
Stochastic-3D	lattice	0	3D	Zykov, Lipson (Cornell)	2005
Molecubes	chain	1	3D	Zykov, Mytilinaios, Lipson (Cornell)	2005
Prog. Parts	lattice	0	2D	Klavins, (U. Washington)	2005
Miche	lattice	0	3D	Rus et al., (MIT)	2006
GZ-I Modules	Chain	1	3D	Zhang & Gonzalez-Gomez (U. Hamburg, UAM)	2006
Odin	Hybrid	3	3D	Lyder et al., Modular Robotics Research Lab, (USD)	2008
Odin	Hybird	3	3D	Lyder et al., Modular RoboticsResearch Lab, (USD)	2008
Evolve	Chain	2	3D	Chang Fanxi, Francis (NUS)	2008
Roombots	Hybird	3	3D	Sproewitz, Moeckel, Ijspeert, BioroboticsLabaratory (EPFL)	2009

Table 2
Electrical and Mechanical characteristics of Reconfigurable Robots[21].

Names of Robot	*Electrical characteristics*		*Mechanical characteristics*	
	CPU On-board	*Power On-board*	*Dimension*	*Attachment Method*
USC/ISI, CONTRO	Yes	Yes	3D	Mechanical, SMA
Stanford PolyPod	Yes	No	3D	Mechanical
PARC PolyBot	Yes	No	3D	Mechanical, SMA
JHU Metamorphic	Yes	No	2D	Mechanical
Dartmouth, Crystalline	Yes	Yes	2D	Mechanical
MEL, Fractum	Yes	No	2D	Electro Magnets
MEL, Micro-unit	Yes	No	2D	Mechanical
RIKEN, Vertical	No	Yes	2D	Permanent Magnets
PARC, Telecube	n/a	n/a	3D	Switching Permanent Magnets
MEL, 3D-Unit	No	No	3D	Mechanical
MEL, MTRAN	Yes	Mo	3D	Permanent Magnets, SMA
Dartmouth, Molucule	Yes	No	3D	Mechanical
CMU, I-Cubes	Yes	Yes	3D	Mechanical

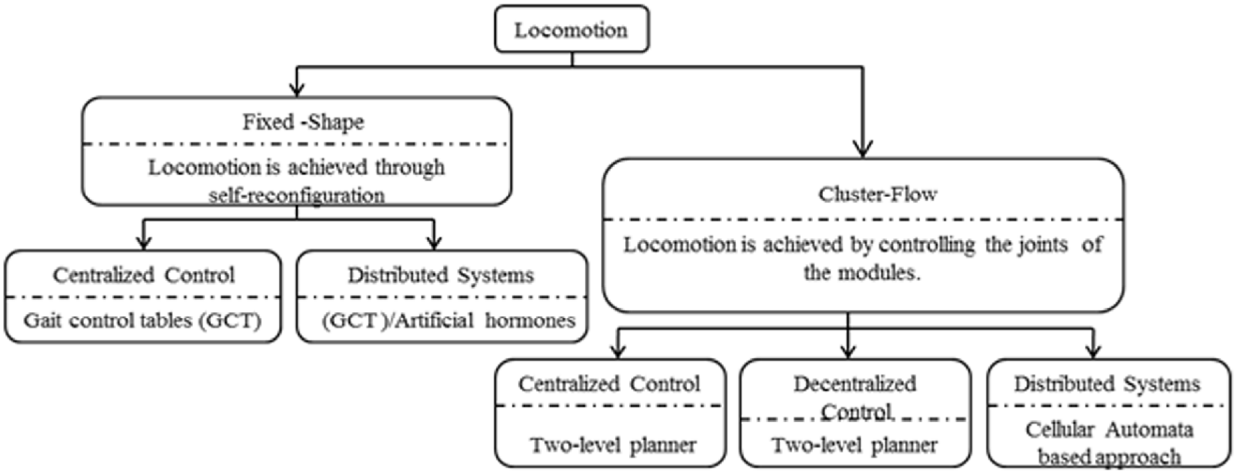


Figure 1: Locomotion systems for Reconfigurable Robots[21].

The hierarchy of modular robots is shown in Fig. 1. Modular Robots is a robot which consists of several modules. If a modulebreaks, it can be identified and replaced in a relatively short time, whereas innon-modular robots the entire robot will be replaced. In Reconfigurable modular robots, the modules are independent and have high degree of homogeneity [22-25]. The reconfigurable modular robot is assumed tohave a fixed shape at run-time, but in off-line it can be reconfigured into differentshapes and sizes. The possibility of changing the shape and size of the robot increases robot's versatility. Dynamically reconfigurable modular robots can be reconfigured at run-time. This happens because the modules have functionality to detect detachmentsand attachments of modules at run-time, and potentially to change behaviordepending on the new configuration. Designing the module morphology andcontrol software for such a system is challenging.

Modular self-reconfigurable robot systems can also reconfigure their own modules. There are a growing number of modular reconfigurable robotic systems that fit this n-modular profile. These systems claim to have many desirable properties including versatility, robustness. While the number of modules has been large in simulation, the physical implementation of these systems has rarely had more than 10 modules. The rescue operation by the workers in the earthquake-affected areas is very difficult because it involves large area and hence it is time-consuming. This section characterises the situations that arouse in the situation and the problems faced by the rescue team during their rescue operation and how the proposed project will be useful in overcoming these factors. In spite of the great progress achieved in the field of antiseismic mechanics i.e. the improvement of building regulations and their application for new constructions during the last few decades, earthquake as a life threatening factor will continue to exist for many years to come.This is due to the following reasons:

- Replacement of old buildings by new ones that are designed according to new regulations is done at a very slow pace.
- The continuous increase in density and intensity of human activities is a factor that escalates the vulnerability of the socioeconomic web. Thus, part of the improvement achieved by applying new regulations is lost.

The need for bringing the current buildings up to date in terms of safety has not been fully comprehended.But despite the slow process in improving the quality of constructions, the casualties in human lives can be reduced by investing in the human factor. That consists of:

- Training the population on self-protection during an earthquake.
- Creating specialized rescue teams and ensuring their fast and effective intervension.

2.1. Characteristics of a building that has suffered a total collapse

The way a building collapses and its final shape depends on a lot of factors (geometry of the bearing structure, distribution of the non-structural walls, the building materials etc.) Therefore, the final geometry of the ruin that turns into a shapeless mass of concentrated material is expected to be different, even between buildings of similar construction. But in spite of the geometrical dissimilarity, the ruins that result from a total collapse have in common two very important characteristics:

- The existence of a sufficient number of survival spaces.
- The stability of volume of the ruins.

These two characteristics are the principal guide-lines for self-protection and for the rescue operations methodology.

2.2. The Rescue Operation

The general characteristics of the rescue from a building that has suffered total collapse are:

- Increased possibility of serious injuries and loss of consciousness of the trapped.
- Arduous and time consuming procedures for locating the victims.
- The penetration of the ruins and the approach of the victims is a particularly arduous, laborious and time consuming procedure.
- Stability of volume of the ruin that isn’t disturbed even by aftershocks. Therefore the risk of injury of the rescue team is nil.

2.2.1. The problems that must be faced are

- Locating the victim.
- Approaching and delivering the victim.
- Supply the victims with medical care on the spot.
- Removal of massive and heavy construction material.
- Protection of the rescuers and the victims from construction material with poor balance damaged neighbouring buildings, electric wires on the ground, broken water and gas pipes.
- The need for temporary scaffolds, supporting and demolition.

2.2.2. Locating the victims

Finding the exact position of the trapped is of first importance for their swift and safe approach and rescue. The methods in current use and their effectiveness are described as follows:

- Use of sound detecting devices.
- Locating with the use of trained dogs.
- Use of information and on the spot examination.

2.3. Approach

The contribution of this work is to provide a rover with sensor suite for human detection in the urban disaster environment and capable of navigating the difficult terrain. The philosophy of the rover is that the robot should be low cost, semi-autonomous, heterogeneous, and work together under a human coordinator.

This project consists of three main pats. The first step will be to determine the state of the art in rover, with special emphasis on sensors for victim detection.Next, a set of appropriate and complementary sensors will be selected in accordance with chosen criteria, mainly that the sensors be low-cost and lightweight. The selected sensors will be integrated with the rover. This involved developing hardware and low level data acquisition software solutions. Tests will be used to determine the robustness, limitations, and accuracy of each sensor and this data will be used to develop a comprehensive system that fuses the information from all the sensors to determine the location and probability of human presence. Finally, a graphical user interface will be developed to provide useful information back to the human operator while allowing the user the power to interact with individual sensors.

3. METHODOLOGY

In this section mathematical modelling, fabrication and control system of rover is explained. Then, the results are verified using simulation software.

3.1. Rover

Factors to be considered for the design and fabrication of a rover:

- Locomotion performance.
- Comparison.
- Kinematic analysis.
- Metrics.
- Exploration rover.

3.2. Rover Kinematics

- Forward kinematics: used in simulation for the estimation of rover position.
- Inverse kinematics: to derive wheel actuation command for a desired rover motion.
- Rover kinematics: in estimation of wheel-ground contact angles.

A kinematic model as shown in Fig. 2 provides valuable information because the ability of articulated rovers to adapt to uneven terrain makes it difficult to relate rover motion to wheel motion and require the wheels to move at different speeds.

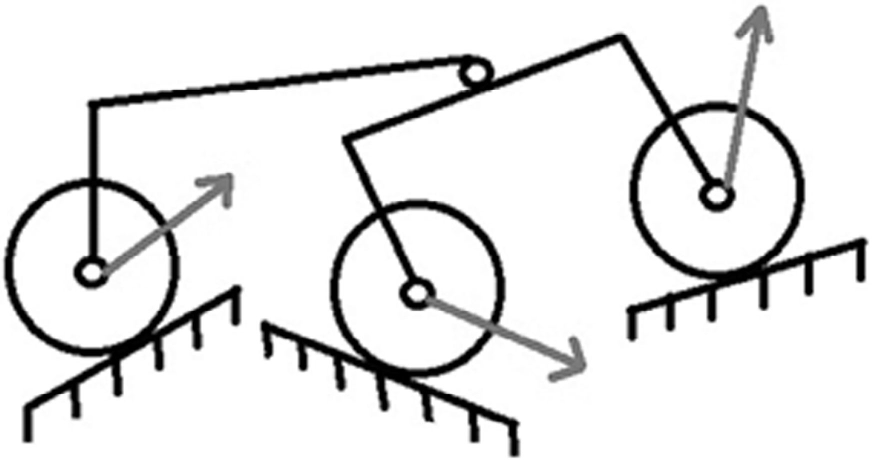


Figure 2: Wheel speeds imposed by kinematics constraints in rough terrains.

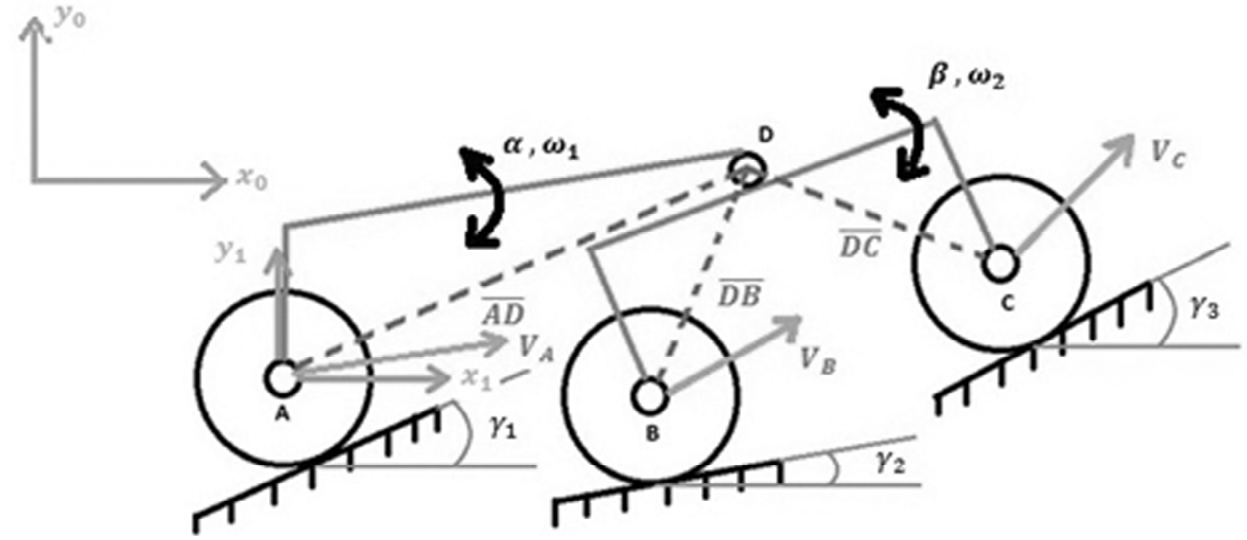


Figure 3: Kinematic model of rover.

In rough terrain, the speed imposed by the kinematics properties of the suspension are different on all wheels given that negative effects like slip are to be avoided as shown in Fig. 3.

$\overline{AD}, \overline{DB}, \overline{DC}$ = Vectors of constant length

γ_1 = Wheel – ground contact angle

α = Orientation of rocker w.r.t interial system

β = Orientation of bogie w.r.t interial system

ω_1, ω_1 = rotational velocities of rocker and bogie

Rough-terrain robots makes use of a suspension mechanism that consists of several rigid elements connected through joints of a certain number of degrees of freedom (DoF) resulting in a structure that has one system DoF.

First ϑ_D is expressed in inertial system coordinates through A, B and C.

$$\vartheta_{DA} = \vartheta_D = \vartheta_A + \omega_1 \times {}^{0}_{1}R\left(\alpha\right)^1 \overline{AD} \tag{1}$$

$$\vartheta_{DB} = \vartheta_D = \vartheta_B + \omega_2 \times {}^{0}_{2}R\left(\beta\right)^1 \overline{DB} \tag{2}$$

$$\vartheta_{DC} = \vartheta_D = \vartheta_C + \omega_2 \times {}^{0}_{2}R\left(\beta\right)^2 \overline{DC} \tag{3}$$

Where, ϑ_i = velocity in i w.r.t interial system

ω_i = rotational velocity of system i w.r.t interial system

${}^{i}_{j}R(m)$ = transformation from system j to i by rotation of angle m

$\overline{XY}_i$ = vector from X to Y expressed in coordinate system i

Equations (1), (2) and (3) are arranged to:

$$\vartheta_{DA} = \vartheta_{DB} : \vartheta_{DA} = \vartheta_{DC}$$

Then, the equation system can be written as,

$$A_x = b \text{ with } x = \left(\vartheta_B,\ \vartheta_C,\ \omega_1,\ \omega_2\right)^T \tag{4}$$

The above equation can be solved for *x* with ϑ_A as input.

If the velocity input is given at B (or) C the system has to be transformed accordingly.

3.3. Performance metrics

a) Slip:

Instantaneous slip (S): is the difference between theoretical velocity due to wheel rotation θ and effective traveling speed $\dot{\theta}$.

$$\frac{r\,\dot{\theta} - v}{r\,\dot{\theta}} \tag{5}$$

To express a total distance S_{tor}[m] a wheel slipped during a full test run. The absolute value of slip is used to include all sliding motions.

$$S_{tor} = \sum_{j=1}^{m} \sum_{i=1}^{n} \left| \Delta pos_{enc_{i,j}} - pos_{\omega c_{i,j}} \right| \tag{6}$$

Where, m = no. of measurements

n = no. of wheels

$\Delta pos_{\omega c}$ = effective displacement

Δpos_{enc} = measured displacement based on wheel rotation.

b) Velocity constraint violation (VCV):

- VCV is a measure for the risk of violating kinematic constraints through deviation of each wheel from the ideal velocity and should therefore be as small as possible.
- VCV is an indicator of how good a suspension system is able to adapt to the system.
- ‘v’ is defined for each wheel as the ratio between ideal velocity V_{kin} and reference velocity v.
- Standard deviation

$$\sigma_v = \left(\frac{1}{n} \sum_{i=1}^{n} \left(V_i - \bar{V}\right)^2 \right)^{1/2} \tag{7}$$

For an m-wheeled robot ((m -1) × m) values of v can be calculated.

$$VCV = \frac{1}{m(m-1)} \sum_{j=1}^{m} \sum_{i=1}^{m-1} \left(\sigma_v\right)_{i,j} \tag{8}$$

Since VCV is a metric for theoretical performance analysis, it is used in simulation only.

c) Mean torque $\left(\bar{T}\right)$:

Is used as a parameter for validation of the VCV metric

$$T_w = I.k_T.\eta.\frac{n}{1000} \tag{9}$$

Where, I = current (A)

k_T = torque constant (m Nm/A)

η = efficiency of gearbox

n = reduction ratio of gearbox

3.3.1. Open Control Platform

This section presents an open loop control platform (OLCP) which provides interaction among modules and supports dynamic reconfiguration and customization of modules in real time.The challenge addressed by the OLCP is to deal with the complexity of integrating these modules in an unknown environment with drastic conditions.It consists of multiple layers of application interfaces that increase in abstraction and become more domain specific at the higher layers as shown in Fig. 4. In other words, at each level, abstract interfaces are defined to provide access to the underlying functionality while hiding details of how that functionality is implemented. Each layer builds on the modules defined in lower layers. In the bottommost “core” layer, the OLCP weights from and outspreads new advances in real-time computation which allow distributed, heterogeneous modules to communicate asynchronously in real time.

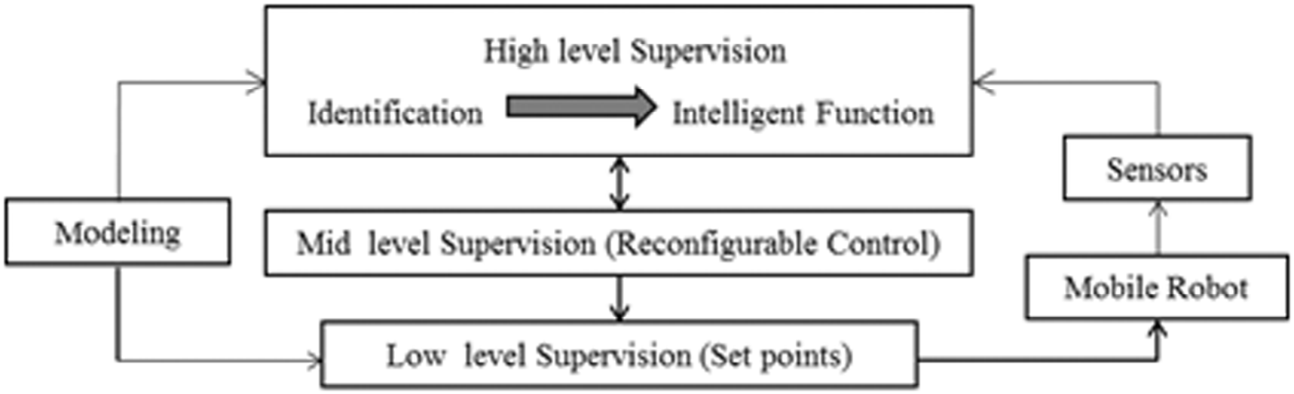


Figure 4: Architecture for Reconfigurable Robots.

3.4. Rover fabricated model

Using solidworks software, a 3D model of the proposed robot is generated as shown in Fig. 5 to Fig. 7.

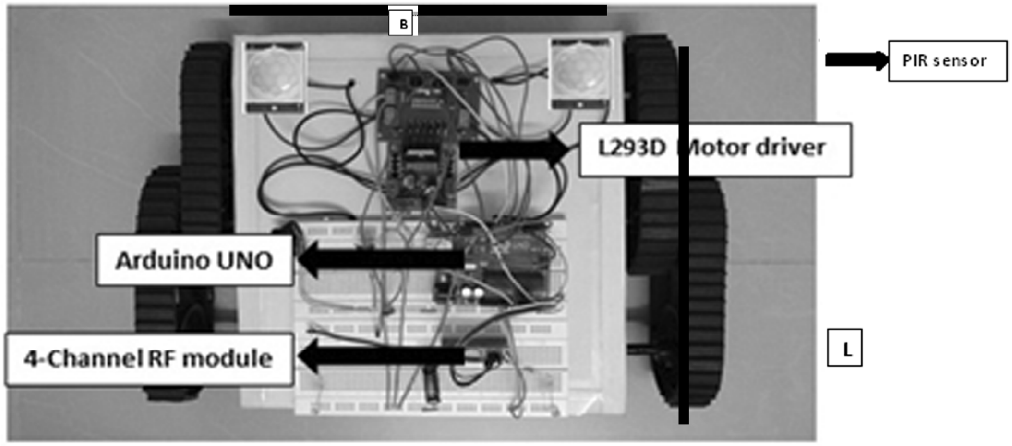


Figure 5: Top view of rover

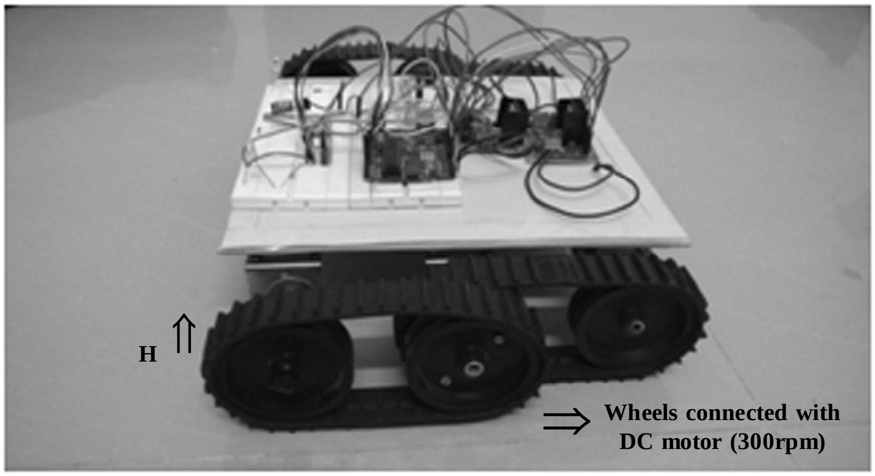


Figure 6: Side view of rover showing sprocket wheel arrangement.

Table 3
Rover specification

Parameter	*Dimension*	*Unit*
L	250	mm
B	250	mm
H	80	mm
Wheel diameter (d)	70	mm
Wheel width (b)	20	mm
Rover weight	3.2	kg

3.5. Rover control system

The control system for rover is constructed by using these four main components:

i. Arduino UNO.
ii. RF (Radio Frequency 4 channel) Module.
iii. L293 Motor Driver. (connects up to 4 bi-directional DC motors)
iv. DC Motors (300rpm, 12v, 6mm shaft, 0.5 kg cm torque).

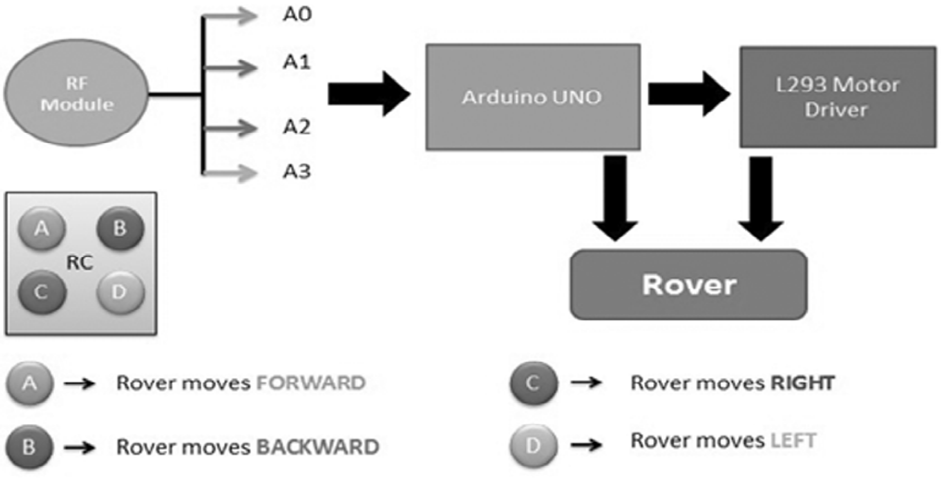


Figure 7: Control system of rover using 4-channel RF module.

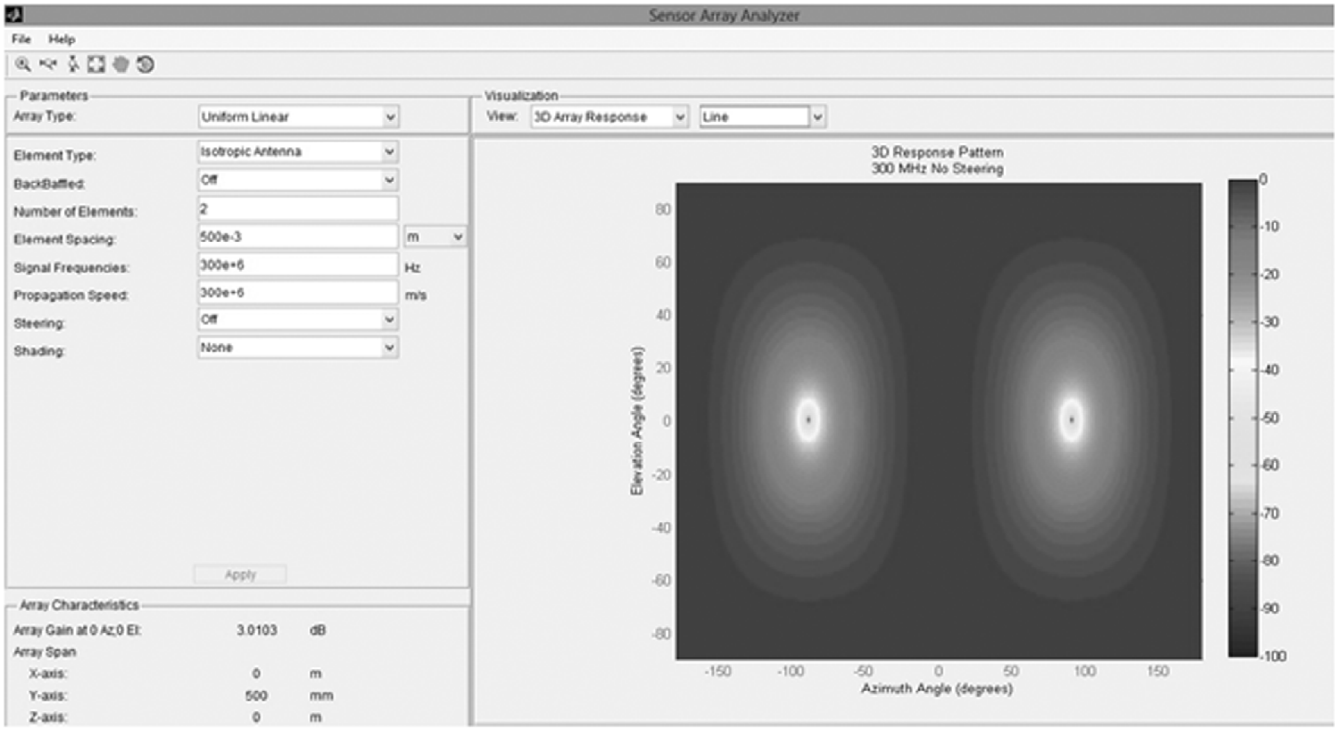
Each button in the RF module remote is defined as an input pinmode in the Arduino program for it to control the direction of rotation of motor.When button ‘A’ is pressed in the remote all the four motors has to get activated and rotate in forward direction. Similarly, if button ‘B’ is pressed all the four motors will rotate back thus, making the rover move in forward and backward direction. And for left and right turn either side of the motors gets activated when button ‘C’ (or) ‘D’ is pressed. Like for right turn two motors placed in LHS of rover gets activated and vice-versa for left turn.

4. EXPERIMENTAL AND SIMULATION RESULTS

The rover is made to move forward for a distance of 5 meters and to take a 180 degree turn in 3 steps i.e. of 60 degree turn. At every step, data from every sensor are taken. Motion is calculated in the normal view; in IR view, the size of the blob and its motion are computed; state of the pyroelectric sensor is read. At the end of the panorama, sound is recording and voice detection is performed. Then the probability to have a human is computed for every step with all the data of the sensor stored in memory. At the end, the user can decide to which way to go where there is highest probability to have a human. For camera a phone can be converted to the viewing camera by using IP webcam software in order to get live feed from the environment to the monitor of a computer. It just requires an IP address generated in the software and wifi to connect. The physical parameters of a victim that we can detect using different kinds of sensors are:

- Voice
- Temperature
- Clothing texture
- Motion
- Scent
- Skin colour
- Shape

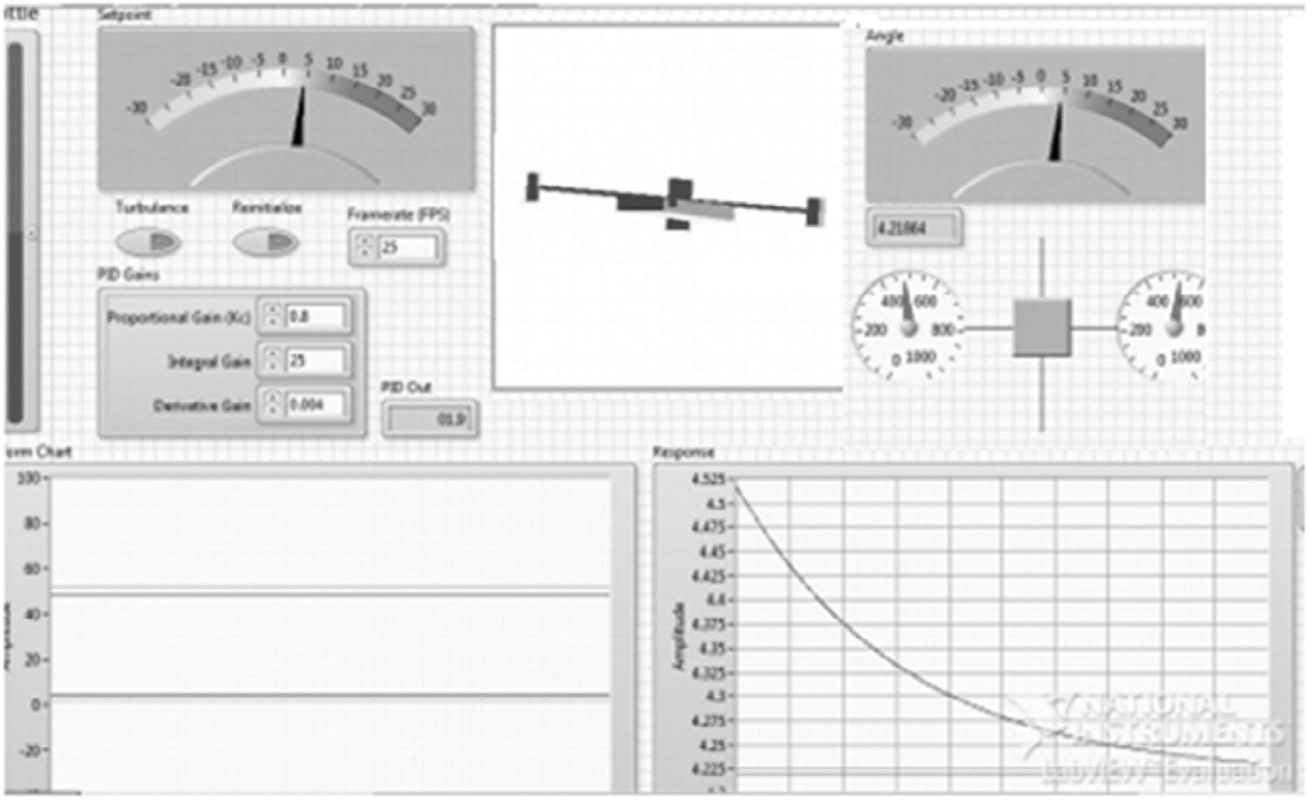
PIR sensors are commonly used with a variety of sensors in diverse applications. It’s been found that the performance of the identification system in terms of the optimal element number of the lens array, the



Array Type: Uniform Linear
View: 3D Array Response
Line
Element Type: Isotropic Antenna
BackBaffled: Off
Number of Elements: 2
Element Spacing: 500e-3 m
Signal Frequencies: 300e+6 Hz
Propagation Speed: 300e+6 m/s
Steering: Off
Shading: None

Array Characteristics
Array Gain at 0 Az,0 El: 3.0103 dB
Array Span
X-axis: 0 m
Y-axis: 500 mm
Z-axis: 0 m

Figure 8: MATLAB Sensor Array Analyser of twoPIR sensors when a human is detected.



Framerate (FPS) 25

Proportional Gain (Kc) 0.8

Integral Gain 25

Derivative Gain 0.004

PID Out 01.9

4.21864

Figure 9: Simulator for rover system in LabVIEW

height of the sensor location, the sensor-to-object distance and walking speed.MATLAB Sensor Array Analyser of two PIR sensors when a human is detected is shown in Fig. 8.

The average recognition rates for 10 persons are 91% and 78.5% in the path-dependent and path independent cases, respectively. The simulation results show that the robot sensor could roughly detect the presence of human and the robot body module could change its shape symmetrically. This experiment demonstrated that the robot body shape change algorithm was feasible and the control program worked rightly. The robot sensor needs further work to acquire the more accurate void shape information in a real environment. In addition, the robot body shape change mechanism needs more powerful actuators. Further, the simulator for rover system is developed in LabVIEW as shown in Fig. 9.

5. CONCLUSION AND FUTURE WORK

There are a few areas, which are deemed to be in need of further work in the future. The first concerns the distribution of forces generated by the robot body acting against the void wall because of the restriction on a symmetrical change of the robot body shape. This will influence the robot traction performance when the robot body does not fit the void very well and some parts of the robot body do not contact with the void wall. The aim of this research was to provide a low cost rescue robot for human detection in a disaster environment. Though, the existing Urban Search and Rescue Robots are equipped with various sensors, but the problem with them is the cost. The sensors used in the development of this project are easily available and cost effective. In this paper, a new method for detecting surviving humans in destructed environments using simulated autonomous robot is proposed. The robot uses two levels of sensing in order to achieve higher cost-effectiveness in the detecting process in terms of the actual cost of equipment, the processing cost, the communication cost, the storage cost, and the power cost. The first level is a Pyroelectric Infrared (PIR) sensor that is used as the primary sensor in order to detect the existence of alive human stuck under the debris caused during the disaster. The second level is by using a simple camera sending live feed to check for human presence through naked eye of the controller. Since the system developed is a low cost system therefore it has a wide future scope. Though many systems with a wide range of sensors have been developed, but there are many problems faced by them such as cost, size, environment difficulties etc.

REFERENCES

[1] Gu, H., Wang, Z., Wang, H.:Shape Reconfigurable Mechanism of an Earthquake Rescue Robot. IEEE International Conference in Mechatronics and Automation,3 (2005) 1145-1150.

[2] Aghili, F., Parsa, K.: A Reconfigurable Robot with Lockable Cylindrical Joints. IEEE Transactions on Robotics, 25(4)(2009) 785-797.

[3] Hirose, S., Morishima, A.: Design and Control of a Mobile Robot with an Articulated Body. The International Journal of Robotics Research,9(2)(1990) 99-114.

[4] Tarokh, M., McDermott, G.J.: Kinematics Modelling and Analyses of Articulated Rovers. IEEE Transactions on Robotics, 21(4) (2005) 539-553.

[5] Kumar, P. and Pathak, P.M.: Dynamic Modeling, Simulation and Velocity Control of Rocker-Bogie Rover for Space Exploration. Advanced Engineering and Computational Methodologies for Intelligent Mechatronics and Robotics, (2013) 103.

[6] Guanghua, Z., Zhicheng, D., Wei, W.: Realization of a Modular Reconfigurable Robot for Rough Terrain. In Proceedings of the 2006 IEEE International Conference on Mechatronics and Automation (2006)289-294.

[7] Zhang, H., Deng, Z., Wang, W., Zhang, J.,Zong, G.: Locomotion Capabilities of a Novel Reconfigurable Robot with 3 Dof Active Joints for Rugged Terrain. In IEEE/RSJ International Conference on Intelligent Robots and Systems (2006) 5588-5593.

[8] Yim, M., White, P., Park, M., Sastra, J.: Modular Self-reconfigurable Robots. In Encyclopedia of complexity and systems science,Springer New York (2009) 5618-5631.

[9] Wu, Q., Liu, S., Cao, G., Fei, Y.: Mechatronics Design of a Modular Self-Reconfigurable and Self-repair Robot. In IEEE International Conference on Control and Automation, (2007) 2243-2247.

[10] Voyles, R.M., Godzdanker, R.: Reconfigurable Robots with Heterogeneous Drive Mechanisms: The Kinematics of the Heterogeneous Differential Drive. In IEEE/RSJ International Conference onIntelligent Robots and Systems (2010) 1340-1346.

[11] Luukkonen, T.: Modelling and Control of Quadcopter. Independent Research Project in Applied Mathematics, Espoo(2011).

[12] Khan, M.: Quadcopter Flight Dynamics. International Journal of Science and Technology Research, (2014)130-135.

[13] Hoffmann, G.M., Huang, H., Waslander, S.L., Tomlin, C.J.: QuadrotorHelicopter Flight Dynamics and Control: Theory and Experiment. In Proc. of the AIAA Guidance, Navigation, and Control Conference 2(2007).

[14] Huang, H., Hoffmann, G.M., Waslander, S.L., Tomlin, C.J.: Aerodynamics and Control of Autonomous Quadrotor Helicopters in Aggressive Maneuvering. In IEEE International Conference on Robotics and Automation (2009)3277-3282.

[15] Choi-Fitzpatrick, A., Juskauskas, T.: Up in the Air: Applying the Jacobs Crowd Formula to Drone Imagery. Procedia Engineering, 107(2015) 273-281.

[16] Thueer, T.:Kinematic Analysis and Comparison of Wheeled Locomotion Performance. Eidgenossische Technische Hochschule Zürich, Autonomous Systems Lab (2008).

[17] Habib, S., Saeed, M.: A MODTRONIX-Based Multi-terrain and Surveillance Robot. In 12th International Conference on Frontiers of Information Technology (2014) 67-72.

[18] Theeravithayangkura, C., Takubo, T., Ohara, K., Mae, Y., Arai, T.: Dynamic rolling-walk Motion by the Limb Mechanism Robot Asterisk.Advanced Robotics 25(1-2)(2011)75-91.

[19] Nagatani, K., Yamasaki, A., Yoshida, K., Adachi, T.: Development and Control Method of Six-wheel Robot with Rocker Structure. InIEEE International Workshop onSafety, Security and Rescue Robotics (2007)1-6.

[20] Dian, S., Liu, T., Liang, Y., Liang, M., Zhen, W.: A Novel Shrimp Rover-based Mobile Robot for Monitoring Tunnel Power Cables. InInternational Conference on Mechatronics and Automation (2011) 887-892.

[21] Madhevan, B., Sreekumar, M.: Structures and characteristics in reconfigurable modularrobots. Advances in Reconfigurable Mechanisms and Robots I. Springer, (2012) 526-534.

[22] Madhevan, B., Sreekumar, M.: Tracking algorithm using leader follower approach for multirobots. Procedia Engineering. Elsevier, (64) (2013) 1426-1435.

[23] Madhevan, B., Sreekumar, M.: Analysis of communication delay and packet loss during localization among multi mobile robots using leader follower approach. Advances in Intelligent Systems and Computing, (385) (2014) 3-12.

[24] Von Neumann J.: Theory of Self-Reproducing Automata. Urbana, Univ. Illinois Press, (1966).

[25] Jones R., Cherry A., Farrall S.: Application of Intelligent Control in Automotive Vehicles. Proc. of Control, (1994)159-164.

[26] RoderichGrob,: Autonomous Self-Assembly in Swarm-Bots. IEEE Transactions on Robotics 22(6) (2006) 1115-1130.

[27] Mark Yim, Paul White, Michael Park, Jimmy Sastra,: Modular Self-Reconfigurable Robots. Springer Magazine (2004)19-32.