Design of Reconfigurable Multi-Agent Robots for Urban Reconnaissance

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ABSTRACT

Reconnaissance, survey and inspection are critical areas that can lead to catastrophic consequences if they are not accomplished effectively. This paper proposes a solution to urban survey, reconnaissance and inspection by combining several positive attributes of different locomotion types into one agent able to climb and to roll. Reconfigurable and modular approaches combined with suction cups or magnets are considered to achieve the goal and provide access to a wide range of areas.

I. INTRODUCTION

Small multi-agent autonomous underactuated robots able to perform urban survey/inspection and to function in place of living agents by carrying out a variety of tasks autonomously or with a minimum of human intervention are highly desirable. Presently the locomotion of most robotic systems can be divided into three main categories: rolling, reconfigurable, and walking. While really effective, a rolling robot is restricted to flat horizontal and low grade surfaces. On the other hand, a walking robot is able to climb and access difficult to reach areas. But it is often characterized as slow and having cumbersome motion on flat to low grade surfaces. Finally reconfigurable/modular robots display a wide range of locomotion and ability to adapt to a new task by altering their configuration. On the downside, they require many actuators, a lot of power and provide very little room for payload.

In the present research, two new innovative designs of a reconfigurable and modular robot are presented towards achieving the desired characteristics of autonomous and underactuation. The mechanical design and sensor suite of the individual agents is presented as well as the conceptual implementation of the robots.

II. BACKGROUND

A brief description of already available robots is first discussed where focus is placed on the locomotion types used. Ground based robots can be divided into three types of locomotion: wheeled/tracked robots, reconfigurable/modular robots and walking robots.

A. Wheeled/tracked Robots

Wheeled robots are often used and can be considered as the most common and most effective type of locomotion. The main problem is that wheeled robots are restricted to flat horizontal surfaces. Some times bigger robots do have the capability to climb stairs but that is the most climbing they can achieve.

The Ranger and the Scouts robots, developed at the University of Minnesota are a unique combination of two robots. They are the perfect example of the limitation wheeled robots face during reconnaissance and also a great display of ingenuity to overcome these limitations. The robots paired purpose is surveillance. They have the ability to be radio controlled and send video feedback to the operator through wireless communication. The Ranger is a larger robot that can deploy up to 10 Scouts.

Figure 1 illustrates the Ranger and its counterpart the Scout. The Scout is a smaller robot (diameter of 40mm and 110mm in length) that possesses two types of locomotion. The first is rolling using two wheels mounted at each extremity of the cylinder shaped robot. This allows an effective motion on flat surfaces. In case an obstacle is encountered the Scout can jump over it using a spring mechanism. The uniqueness comes from the ability of the Ranger to deploy the Scout by shooting it through a window or into the targeted area. While a very smart solution, this is an intrusive way of entering an area (breaking through a window, Figure 1) and is not suited for any undetected applications.
The tracked robot also fits in the category of rolling robots. The portable urban reconnaissance robot at the California Institute of Technology is a very interesting robot. A combination of two tracks allows high maneuverability and mobility. The PackBot was developed by IRobot Inc. Figure 2 shows PackBot climbing stairs, this is the limited essence of climbing that wheeled robots can achieve. The component enabling stair climbing is the innovative tracked arm allowing for extreme maneuverability, see Figure 3.

B. Reconfigurable Robots

Probably one of the most fascinating area of robotics is reconfigurable robotics. Characterized by an ability to change shape and adapt to a situation they offer a real multitude of solutions to unknown situations occurring during a mission. A reconfigurable robot often uses a series of identical modules having few degrees of freedom. Combined they create a chain of robots with high mobility and high flexibility. The Conro robot, for example, can reconfigure its modules in order to move in a snake like motion or rearrange into a walking robot configuration having four legs as illustrated in Figure 4. Each Conro module can be considered as a small autonomous robot by itself. The same type of robots can be reconfigure to a close loop and can role or climb up stairs in a fashion similar to tracked locomotion. Figure 5 illustrate a stair climbing reconfigurable robot.

C. Walking Robots

Walking robots is the last main category of ground-based locomotion. They are often inspired by animal or human behavior and can be biped, quadruped or 6-plus legged robots. For example the cricket based robot seen in Figure 6.

Another example of a nature inspired robot or locomotion is the human like biped walking robot seen in Figure 7. The six legged robot is also a platform widely utilized and researched, see Figure 8.
The last type considered are climbing robots which are placed in this category because they are often walking robots. The most impressive one is the climbing robot developed at Michigan State University, see Figure 9. This robot was designed to perform reconnaissance and uses suction cups in order to climb walls. It uses underactuation in order to reduce the weight of the robot by eliminating some of the actuators.

In summary, wheeled robots are the best solution for flat surfaces but can not access any elevated areas. Walking robots can climb but are usually really slow and clumsy on flat surfaces. They require a lot of power and sensors to keep their balance. Reconfigurable robots are usually slow, requiring a lot of computing power and sensors due to the fact that they have many modules. Those modules are usually useless on their own. To conclude, there is a clear need for a hybrid solution.

III. NEW PROPOSED DESIGNS

It is currently difficult to find an inexpensive robot that is both efficient on flat horizontal or low grade flat surface and able to access elevated areas. Two new design concepts are presented: 3DRP (Three Dimension Reconfigurable Platform) and 3DMP (Three Dimension Modular Platform). Those two approaches are being designed, prototyped and tested in order to determine which robot is the best fit for urban survey and sensitive inspection of devices. The current stage of development of these robots is design and alpha prototyping.

A. 3-D Reconfigurable Platform.

The 3DRP is a climbing robot that has the ability to reconfigure into a rolling wheeled robot. The robot is designed to be in the rolling configuration 95% of the time. During that time the robot is limited to flat surfaces with low grade slopes but it is very agile and efficient. The skid controlled wheels allow for the robot to rotate upon itself, and its small size allows it to reach almost anywhere.

Figure 10 shows a representation of 3DRP in its two configuration modes. The climbing Figure 10 (a) is done by activating alternately each suction cup, grounding the corresponding robot link. The revolute joint is used to swing the free end of the robot to a desired position between switching suction cup activation. Each swinging maneuver results in a circular arc trajectory of the free end of robot. Figure 10 (b) shows 3DRP into the rolling configuration where it is controlled using skid steering. The 3DRP can turn on the spot and shows high maneuverability. The back wheel is not actuated and, like the front wheels, is an omni wheel. The omni wheel is used in the back to allow for repeatability during turning. In the front the omni wheels are used to allow the “wings” of the robots to deploy without being affected by the friction between wheel and surface.

Figure 11 depicts the kinematic diagram of the robot. The mobility of the robot, when one suction cup or magnet is activated, attaching to the ground, consists of four degrees of freedom. In order to reduce weight, one actuator is removed. By reducing the number of actuators under actuation results; thus reducing the weight and power requirements of the robot. Specially, one actuator is used to drive both $\theta_1$ and $\theta_2$ with equal angle. The 3DRP can be considered to be a serial robot with revolute joints around $S_1$, $S_2$, $S_3$, and $S_4$ axes. The revolute joints around $S_1$ and $S_4$ have permanent rotation joints which are also used to drive the wheels when in its rolling configuration. Figure 12 shows the constant kinematics parameters of the 3DRP robot. The effective circular arc trajectory radius, Figure 13, for the swinging maneuver is equal to:

$$\text{arc radius} = a_{12} + a_{23} + a_{34}$$
These parameters and joint variables can be selected in the design phase and adjusted depending on the application and payload. The payload is envisioned to be mounted on the wheel encasement.

**B. Modular Approach**

A second robot is also under investigation and is probably the most promising robot out of the two. An Isometric representation of the robot is shown in Figure 14. The 3DMP is a simple, effective three wheeled platform for horizontal flat surfaces. The two front wheels are actuated using small widely available RC servomotors. The third contact point with the floor is made using a ball transfer. By having one ball transfer on each side of the robot, it allows the robot to flip over and to operate on both sides, which in turn simplifies the climbing algorithm. Figure 15, shows the packaging of the required components on the robot. They are sandwiched between two delrin plates in order to protect the electronics.

Figures 16 and 17 shows two 3DMP robots after docking and after flipping the other module 180°. Figure 18 depicts the kinematics of the two docked 3DMP robots, and the corresponding constant parameters of the paired 3DMP robots.
Figure 14. Isometric of 3DMP.

Figure 15. Inside Components of 3DMP.

Figure 16. Two 3DMP Docked Together.

Figure 17. Two 3DMP One Flip on Top of the Other.

Figure 18. (a) Kinematics. (b) Kinematic Parameter. 3DMP Robot.
When one of the suction cups is grounded the mobility of the two combined robots corresponds to four degree of freedom. As can be noted, the kinematics of 3DMP pairs and 3DRP are similar in nature with exception of the $S_1$ and $S_4$ joint are 90° different kinematically. The constant parameters and variables are:

<table>
<thead>
<tr>
<th>Link Length, in</th>
<th>Joint Angle</th>
</tr>
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<tbody>
<tr>
<td>$a_{01} = 2.00$</td>
<td>$\theta_1 =$ variable</td>
</tr>
<tr>
<td>$a_{12} = 4.00$</td>
<td>$\theta_2 =$ variable</td>
</tr>
<tr>
<td>$a_{23} = 4.00$</td>
<td>$\theta_3 =$ variable</td>
</tr>
<tr>
<td>$a_{34} = 4.00$</td>
<td>$\theta_4 =$ variable</td>
</tr>
<tr>
<td>$a_{45} = 2.00$</td>
<td></td>
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The maximum travel distance on a flat horizontal or vertical surface (with section cup flat on the surface) is:

\[
\text{max travel} = a_{12} + a_{23} + a_{34}
\]

The minimum distance of travel of is $a_{23}$. All joint angles can rotate a maximum of 180°.

During climbing, using a suction cup or magnet, a moment results on the suction cup where, to offset that moment, a support around the anchor point is implemented, see Figure 21.

![Figure 21. Support to Reduce the Moment Arm.](image)

In Figures 22 and 23, the mobility scenarios of the two robots (3DMP and 3DRP) are illustrated in the climbing of a desk, showing two different approaches to reach the targeted area. Figure 24 shows the climbing of the 3DMP robot in more details.
Figure 22. The Two Robots Going From Rolling to Climbing.

Figure 23. Mission Architecture.
Figure 24. The Two Robots Reconfiguring from Rolling to Climbing.

1. Approach and Detect Wall
2. Dock and Attach to Wall
3. Flip 3DMP Module-B
4. Module-B Clamps to Wall And Module-A Releases
5. Alternate Flipping Module-A and Module-B
6. Top Edge Reached Maneuver to Clamp to Top Surface
7. Module-B Clamped to Top Surface Module-A Flipped
8. Return to Wheeled Configuration
9. Undocked and 3DMP’s Proceed to Their Target Destinations
IV. HARDWARE AND APPLICATIONS

A. Testing Robots.

A rolling robot was designed and custom built in order to test the path planning and docking algorithms. Two robots were fabricated to have the same skid control configuration as the 3DRP and 3DMP will be 95% of the time. Figure 25 depicts the 2DTP (2D Test Platform) and its major components.

![2DTP Robot](image)

The first scenario under investigation is the survey for a small rectangular area. The path planning algorithm generates the coordinated multi-agent formation trajectories in order to completely cover the area to be surveyed as illustrated in Figure 26. Figure 27 shows the two completed 2DTP and a possible formation in which they will perform survey.

![Multi-Agent Formation Path Planning and Control Surveying](image)

The main controller is located on a computer and feeds the position to the agent through wireless communication. The feedback is done using a positioning system created by PhaseSpace, Inc. allowing the tracking of several LEDs at a maximum frequency of 220fps. The data is fed back as a X, Y, Z position for each LED. The test bed with one 2DTP robot being tracked by 3 cameras is shown in Figure 28. Figure 29 depicts the overall architecture of the system.

![Test Bed and Camera Tracking One 2dTP Robot](image)

Applications of the presented systems are in health monitoring for shuttles, planes and ships. They could also be used for homeland security performing reconnaissance and survey in hard to reach areas such as a vent system. In addition the system could be used to perform inspection in dangerous or contaminated areas (e.g., nuclear plant).
VI. CONCLUSIONS

Different types of locomotion were presented in this paper. It is obvious that there are few solutions for an inexpensive small platform able to perform efficiently on horizontal flat surfaces and also be able to reach elevated areas. Thus two platforms were presented: 3DMP and 3DRP. They are both designed to accomplish a common goal but both using different techniques. The 3DRP robot can do it on its own by achieving reconfiguration and the 3DMP robot needs two agents using modularity.

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