On the Development of a Novel Urban Search and Rescue Robot

ENS Bryan M. Hudock, USNR
Bradley E. Bishop
Frederick L. Crabbe
United States Naval Academy
105 Maryland Ave (Stop 14a)
Annapolis, MD 21402

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Abstract-- **This paper concerns the development of a novel robotic platform for Urban Search and Rescue (USAR) efforts. The main facets of this work involve the design and construction of a new robot morphology and a physical simulation to be used for developing controllers for semi-autonomous (supervisory) operation.**

I. INTRODUCTION

Recovering survivors from a collapsed building has proven to be one of the more daunting challenges that face rescue workers in today's world. Survivors trapped in a rubble pile generally have 48 hours before they will succumb to dehydration and the elements [1]. Unfortunately, the environment of urban search and rescue (USAR) does not lend itself to speedy reconnaissance or retrieval. The terrain is extremely unstable and the spaces for exploration are often irregular in nature and very confined. Though these challenges often make human rescue efforts deep within the rubble pile prohibitive, a robot designed for urban search and rescue would be very well suited to the problem.

Robots have already proven their worth in urban search and rescue, most notably in the aftermath of the September 11th, 2001 disaster. The combined efforts of Professor Robin Murphy, a computer scientist at the University of South Florida, and Lt. Col (ret) John Blitch, culminated in the creation of the Center for Robot Assisted Search and Rescue (CRASAR), which coordinates and assists robotic search and rescue efforts [2] Though these and other undertakings have shown the potential of a robot in the urban search and rescue environment, there is still room for significant improvement. Most notably, a unique structure and method of mobility could result in a vehicle much improved over existing urban search and rescue robots in terms of range and ability to overcome obstacles.

The primary goal of this project was to develop a robot that was highly mobile, lightweight, and easy to control. The robot was to be designed from the ground up with specific features to combat the irregular terrain found in an urban search and rescue environment. Specifically, the robot was designed to overcome three pre-selected obstacles that represent a sample of the types of impediments found in a collapsed building: irregular terrain, canyon, and ladder (see Fig. 1).

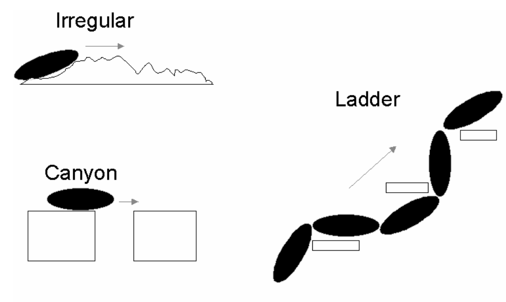

Figure 1: Selected obstacle types

The secondary goal of the project was to develop a simulation that modeled the physical prototype and its environment. This simulation could be used to produce pre-programmed controllers to simplify user input under a supervisory control architecture.

The remainder of the paper is organized as follows: Section II contains the description of the basic robot morphology selected, while Section III includes details of the physical prototype. Results of the physical design are discussed in Section IV. The physical simulation is discussed in Section V, and conclusions given in Section VI.

II. ROBOT MORPHOLOGY

The preliminary step of physical construction was to determine the robot's overall design. There were several factors that affected the overall structure. First, the robot needed to be able to move through the confined spaces often found in a collapsed building. Second, the robot needed to be very flexible in structure in order to easily maneuver over and around obstacles. Third, the robot chassis needed to be designed in such a way as to maximize strength while keeping overall weight as low as possible. Ease of transportation was an important factor for the robot, considering how the debris from a collapsed building could often make it difficult to access an area for search efforts. The final requirement was a versatile means of mobility. As the irregular and unpredictable nature of the environment often called for creative ways of dealing with terrain challenges, a robot with a variety of methods of movement had a greater chance of succeeding in such a difficult setting.

The brief history of robotic involvement in urban search and rescue has seen designs that have almost exclusively relied on wheeled/treaded propulsion [3]. Though there have been alternative designs such as the snake effort by Choset [1], the versatility of a wheel in a variety of terrains combined with its simplicity and reliability have made it the common choice of mobility for search and rescue robots [4]. The addition of treads to a wheeled system has benefits and drawbacks. On the one hand the tread applies force all along its surface, in essence transforming the side of a robot into one large wheel. Though treads generally give robots an advantage in irregular terrain, the added complexity of a tread system and the need for specialized parts often make them prohibitive. In the case of an urban search and rescue robot, the benefits of a tread system in such an irregular environment outweigh the specialization and complexity problems.

A snake-like robot is a serious contender for a successful USAR robot. These robots consist of a series of linked cars, a design that has significant structural flexibility. The concept of jointed cars makes snake-like robots highly adapted to movement in confined spaces. There has been significant past work with snake-like robots (see, e.g., [5] and associated references), although most of this work is not intended for the USAR application.

The robot morphology selected is based on a combination of tracked vehicles and snake-like robots. The robot is made of a series of 'carts,' connected by a 2 DOF joint (pitch, or elevation, and yaw, or heading). The carts themselves have four independent tracks… top left and top right, and bottom left and bottom right. Mounting treads on both the top and bottom of each car in the vehicle enhances mobility in confined areas by allowing the robot to use the roof of the environment along with the floor in order to propel itself forward. Wraparound tracks actually prohibit motion when encountering top-and-bottom obstacles (e.g., when tunneling). See Fig. 2 and Fig. 3. The independent left-right tracks provide differential steering on each cart, which aids in mobility by not relying on strictly serpentine motion (which is not computationally simple nor very efficient). Placing additional tracks on each of the 'side' faces was considered, but the complexity precluded their inclusion in the initial prototype phase. These extra tracks could provide needed traction in case the robot tipped over, although it is anticipated that the device could right itself using only the actuation between the carts.

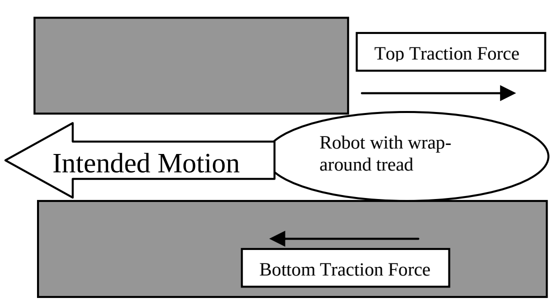

Figure 2: Effect of "wraparound" track

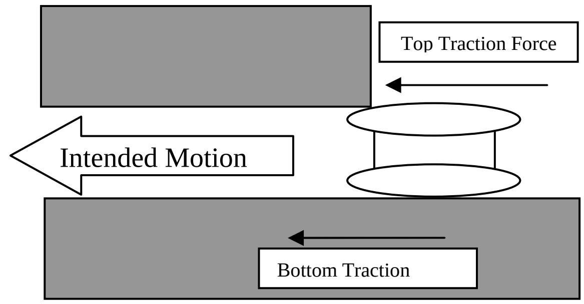

Figure 3: Effect of independent top and bottom tracks

The links between the cars form an extremely important subsystem. Those 2D links need to have some form of *compliance* with respect to the environment. A stick and a chain illustrate both aspects of the compliance concept. A stick is an object with no compliance. The relative position of every section of the stick is always constant, but it has no ability to conform to the environment. A chain conforms to an irregular environment, but it is impossible to control the position of each link in relation to the others.

While it is true that linked units have far more versatility and flexibility than a monolithic structure, and that powered links also provide the ability to perform shape forming with the cars, it is also true that when the links of a snake robot are powered, the robot becomes inflexible and unable to adapt its overall shape to the environment without purposive action from the controller. A robot that automatically conforms to the terrain is much more effective, as it maximizes the amount of contact between the robot and the surface without requiring complex (and challenging) control. On the other hand, a passively compliant robot could not achieve shape forming, as the shape would be dictated by the environment. In order to accomplish both shape forming and compliance, novel pitch-yaw robot joints were designed.

The *selective compliance* joint was based on a simple principle. Selective compliance allows the robot to adjust the level of compliance based on the expected situation and environment. The goal of selective compliance is to keep as many cars in contact with the floor surface as possible, especially over irregular terrain. Achieving this goal involves modifying the portion of the link that controls pitch. Instead of a rigid connection from the motor controlling pitch to the next car, the two entities are connected by a rod, which has a rigid connection on one end and a pin joint on the other. Springs are connected on the top and bottom of the motor shaft, with the other ends of each spring connected to the top and bottom of the back of the car (see Figure 3).

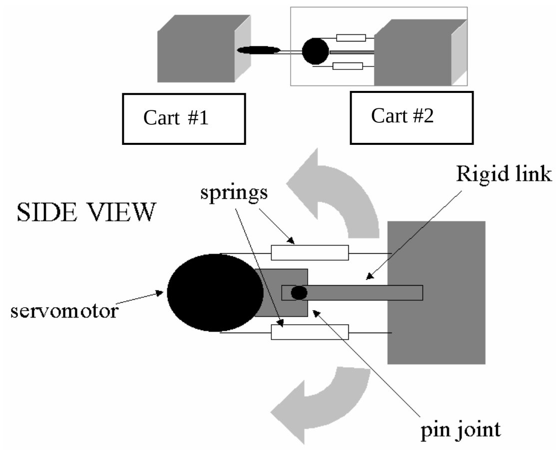

Figure 3: Selective compliance mechanism

Rotating the motor shaft changes the equilibrium position of the car. If the motor shaft rotates counter-clockwise, the equilibrium position of the car rises, and the car lifts. If the motor shaft rotates clockwise, the equilibrium position of the car lowers, creating the opposite effect. The spring-connected joint should also have a large degree of flexibility, especially when compared to a rigid link. When enough force is applied to the body of the car, it should stretch the springs in the link and shift its position. When this force is removed, the springs return to their equilibrium and the car moves back to its original position. Lowering a car's equilibrium point past the floor creates a normal force on the ground greater than the weight of the car.

The selective compliance mechanism results in terrain conformance, which provides better traction than a rigid system without the need for complete control. The spring tensioner allows active control if required, for instance when climbing stairs or levering up to reach a high point. The tensioning of the spring link needs to be carefully controlled. As the link applies force on both cars to which it is attached, too much torque could cause the cars to lift and coil up, defeating forward motion by the robot. Nevertheless, this mechanism represents a major step in increasing mobility in USAR vehicles.

III. PHYSICAL PROTOTYPE

The basic morphology of the robot is of no use if it is not feasible to implement it in a compact and powerful package. In this section, we describe how the basic morphology was developed into a physical prototype, piece-by-piece. The final robot (Fig. 4) consisted of three cars, which was the minimum number needed to accomplish basic link actions such as pitching a single car up or down. Each car was constructed out of ¼" thick plywood and was reinforced by ¼" steel threaded rod. The total weight of the robot was approximately thirteen pounds (with no onboard power supply). The car links had a maximum pitch angle of approximately forty-five degrees, and a yaw (heading) range of motion of fifteen degrees in either direction.

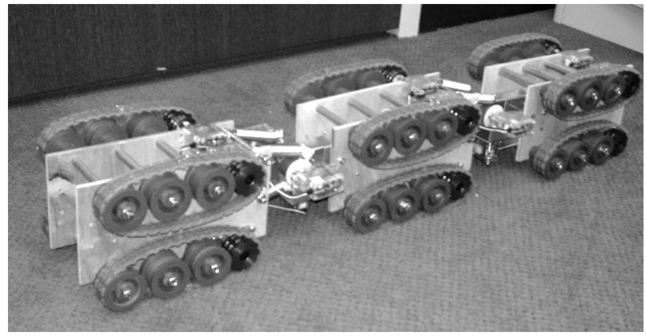

Figure 4: USAR robot prototype

A. Tread Design

The treads would never have left the design table if parts could not have been found that met physical requirements and were within a respectable price range. The treads needed to be strong, durable, and conducive to modification according to the dimensional requirements of the robot. Finding treads that met these requirements proved a much greater challenge than expected. Timing belts manufactured by W.M. Berg proved to be an acceptable solution. The belts were designed to be "no walk," or grooved in more than one direction, such that they would not slip off the side of the pulley. The belts consisted of steel cords surrounded by polyurethane, making them very strong and durable.

The first downside to the timing belt emerged when it came time to splice pieces together into loops to be used as treads. W.M. Berg offered a splicing kit for such purposes. Unfortunately, the manufacturer's splicing system left a large gap in the tread that would have caused unacceptable snags on the contact surface. The splicing kit itself was also very expensive. Consequently, the decision was made to explore other splicing options. Boring small holes at each end of a piece of timing belt and using steel thread to sew the two ends together proved to be a solution.

Surprisingly, the strength of the timing belt proved to be another drawback when it was used as tread. When looped around small objects such as the wheels of the robot, the timing belt's steel cord center acted as a spring that gave the belt a natural tendency to straighten out. This tendency of the timing belt to push outwards further enhanced the normal force contact with an object. However, this characteristic also lessened the contact area between pulley and belt, making it more likely a tread would be thrown, rendering one side of the car useless (although this never occurred during testing due to the 'no-walk' timing belts). A less rigid material under tension would sag and ensure greater consistency of motion.

The tread system included passive idler wheels that were mounted alongside the wheels actually driving the treads. By maintaining contact points and normal forces along the entire length of the bottom of each tread, the idler wheels were the parts that gave the tread its high capability in terms of mobility. Thus the idler wheels needed to be lightweight, but also of a material that could be grooved to provide a continuous path for the tread to follow. PVC plastic was selected for its lightweight yet durable nature, as well as the ease with which it could be lathed and shaped.

B. Motors

The robot design required two different types of motors; one type of motor to power the treads and one type to power the joints between cars. Both types needed to be lightweight DC motors capable of producing high torque. The one significant difference between the two motor types was that the joint motors required position control, while the tread motors needed only speed control. A heavy-duty R/C servomotor was able to accomplish both tasks. Servomotors were perfectly suited to powering the links because the built-in shaft encoders provided accurate positional control. The one drawback to using a servomotor to power the treads was that servomotors have mechanical stops that only allow a range of motion of approximately 180°. Additionally, the feedback loop of the servomotors is controlled by a potentiometer connected to the output shaft. This potentiometer had to be removed or isolated from the circuit, and a resistor bridge put in place to allow for continuous running. With these modifications the servomotor could be used to run continuously [6]. The motor selected was a CS-80MG Pro, made by Cirrus. Weighing only 2 ounces, it is able to deliver 129.8 oz-in of torque at 6 volts. Constructed with metal gears and ball bearings, the servomotor is much more durable than typical servomotors that use plastic gearing.

C. Chassis

In order to optimize the robot's effectiveness, the chassis of each car had to fulfill a few important requirements. First, the chassis needed to be lightweight. This was important not only to increase the ease of transportation, but also to assist in the implementation of a two-degree of freedom link. Assuming a distance of about four inches from servo shaft to vehicle center of mass, a single servomotor was capable of lifting a car that weighed approximately 30 ounces. The chassis had to support three items: the servomotors driving the treads, the idler wheels, and the link structure. One of the benefits of using servomotors to drive the wheels of the vehicle was that the servos could be mounted on a thin piece of material, since the servomotor casing had fabricated holes that allowed it to be bolted in place.

The chassis design eventually selected consisted of two flat sidepieces identical in appearance. Threaded steel rod was run through holes in the two sides. The rods supported the idler wheels while allowing them to freely rotate. Aluminum spacers were placed on the rods to reinforce the sidepieces while maintaining the car's exact dimensions. Aluminum and wood were used to construct the various car prototypes, as they were both adequately strong while costing little in terms of weight.

D. Passive Compliance Joint

The joint formed the most important subsystem of the design. In the initial design, each joint mechanism consisted of four pieces. The first was a bracket that attached to the servomotor that controlled the car's heading to the chassis of the rear car. Mounted on the wheel of the heading servomotor was a second bracket that held the two servomotors controlling pitch. The final two brackets were used to connect a passive wooden pivot to the rear of the front car.

The problem with this initial design was that elevating the front car placed enough torque on the heading servomotor shaft to bend it significantly. The bending of the shaft caused the link to tilt forward and misalign the pitch pieces and also posed the risk of breaking the shaft completely. Consequently, two additional pieces were added to transfer the torque from the servomotor shaft to the chassis of the rear vehicle. A plastic cylinder with a hole in its center was bolted onto the heading servomotor wheel. A bolt was inserted into this hole and held in place by a bracket positioned above the cylinder. The bracket holding the bolt was attached to the rear car chassis. As a result, any impulse of the link to bend forward would be checked by the bolt-cylinder arrangement. The mechanism can be seen in Fig. 5.

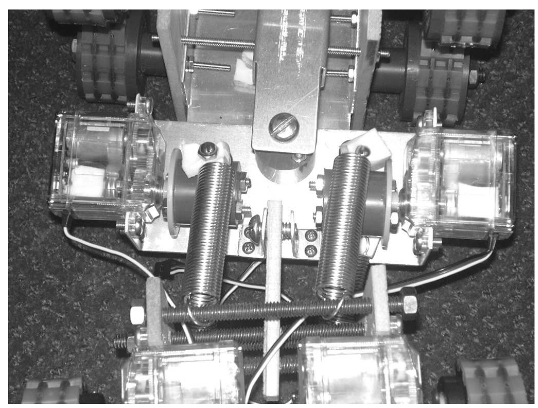

Figure 5: Passive Compliance Joint

IV EVALUATION AND TESTING

To properly evaluate the vehicle, a user interface was designed. This system was based on a single Rabbit microprocessor and a Pontech SV203 board on each cart. Due to the complexity of the system, only simple commands have been tested at this point ("move forward," "pitch up" and "curve").

Overall, the physical prototype performed as expected. The mechanisms of selective compliance and heading control worked as designed. In small, simulated conditions, the vehicle performed well on uneven terrain due to the selective compliance. Shaping was achieved as desired.

The robot's design should prove effective against a canyon obstacle. The use of a powered, 2DOF joint to link each car gives the robot a vertical mobility that should be useful in overcoming horizontal gaps. Using algorithms such as the one developed by Nilsson [7], the robot could be manipulated to achieve an upright position. From this position it could then lunge across the canyon and use the terrain on the other side to pull itself over the gap.

The morphology is also well suited to surmounting a ladder obstacle, in which the robot's only method of traversing would be to wind its way through the rungs (especially for rounded rungs or steep ladders). The robot's ability to use treads on both its top and bottom should allow it to maintain forward motion by using the rungs above and below it for contact. Pitching the car upwards with the powered links should provide the force necessary to maintain contact with a rung located above a car. The robot's unique structural features should give it a large advantage when trying to defeat this difficult obstacle.

V. PHYSICAL SIMULATION

The secondary goal of this project was to develop a flexible simulation that could be used to work towards a genetic algorithm capable of producing optimal pre-programmed supervisory control commands to ease the burden of the user interface. This entailed selecting a capable physics simulation package that included features such as the jointed links that were found on the physical prototype. A robot resembling the physical prototype was built within the simulation, along with various types of obstacles.

Open Dynamics Engine (ODE) was selected as the tool for modeling and simulation. In the words of the author: "ODE is a free, industrial quality library for simulating articulated rigid body dynamics - for example ground vehicles, legged creatures, and moving objects in VR environments. It is fast, flexible, robust and platform independent, with advanced joints, contact with friction, and built-in collision detection"[8].

The final simulated robot was similar to the actual physical prototype. The parameters of the robot, including number of cars, chassis and wheel size, number of wheels, suspension damping, and maximum torque used by the car links could be easily changed. The wheels (which replaced the real tracks for simulation purposes) were independently powered to give each car differential drive.

The ODE simulation was used for a simple genetic algorithm development of user-interface control. The results of those experiments showed that this simulator was adequate to begin development of complex 'drive-by-wire' controllers required for a user to interface to a real vehicle with six cars and 34 degrees of freedom. Results are discussed in [9].

VI. CONCLUSIONS

In this paper, we have described a working prototype USAR robot employing structural features designed to enhance the robot's movement capabilities. The selective compliance joint was a unique feature that had never been applied to existing urban search and rescue robot designs. Its ability to control the relative angles between the cars, while at the same time allowing them a degree of compliance, was critical in creating a design that had a significant degree of flexibility. Dual top and bottom treads significantly enhance mobility in confined spaces and loose rubble. A physical simulation was developed to assist with the design of user interfaces for simple control.

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