Multidisciplinary Senior Design Conference
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Rochester, New York 14623

Project Number: P14219

[M.A.R.S.U.P.I.A.L.] MULTI APPENDAGE ROVER SYSTEM FOR UNMANNED PROBE INTELLIGENCE AND LIFE-SUPPORT

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ABSTRACT

M.A.R.S.U.P.I.A.L. is a multipurpose rover which has the capability to reduce costs, add functionality, and create an all-in-one system which solves the growing need for unmanned assistance. Using a novel track suspension design, the rover platform is well-suited to both indoor and outdoor environments. It is designed to be fast, agile, and rugged; the rover will be able to take on various terrains and adapt to its environment with a multitude of payload capabilities. Using inexpensive radio repeater modules set up in an automatic mesh network, the usable range of the robot can be extended quickly, easily, and seamlessly.

INTRODUCTION

With the evolution of technology in the last few decades, robotics stands out as one of the most prosperous, intriguing, and eventful new fields. With an ever increasing presence in society, robots are taking on a multitude of varied tasks; with each one specialized to find in its own niche. Unmanned ground vehicles (UGVs) are a common type of robot that has the potential for extensive use in many different situations. Currently, however, mobile platforms do not possess the flexibility that is necessary to excel in such diverse work environments. Robotic platforms with permanent attachments do not allow for much variation or venture into additional areas where different platform types would be needed. This creates excess costs and limited capacity in each platform. If instead a single platform can be adapted to any situation, the costs of owning such a robot will be reduced and it may be able to compete at the same level of existing systems even if it requires a higher initial investment.

PROCESS AND DISCUSSION

Robotics in the Field

Robotic platforms are defined as remotely controlled mobile devices that can carry out a variety of tasks normally deemed boring, inefficient, or dangerous to humans. These platforms have a variety of military, agricultural, and commercial applications, which range from search and rescue to farm field seeding and even to cleaning the floor. The current path of robotics is to individually design and fabricate a singular robot that will accomplish the task at hand. This has led to the increased specialization of the field, and while this is suitable for stationary or application-oriented issues, it doesn't provide a robust solution that is capable of reacting to an unknown environment in a multitude of diverse situations.

Current platforms come in a wide range of size and capabilities, with some of the largest being farming and mining equipment. Some very large systems are only semi-automated, such as the GPS-augmented control of tractors and combines, as well as large dump trucks hauling quarry debris. Smaller systems can currently be fully automated safely, such as robotic floor sweepers and warehouse organization systems. And finally, the smallest size of these platforms can be seen in the hands of children and the military; these would be similar to small RC cars that can be used for reconnaissance or the tiny helicopters that can be found in a mall. Most of these systems are relegated to a single, specific purpose, with no opportunity for expansion.

The Payload Solution

A solution to help end the specialization of platforms would be to produce a singular platform that is capable of holding and utilizing multiple attachments. A robust platform may be outfitted to handle any situation it faces. Some current platforms allow for *payload* capabilities, but they are increasingly specialized as well, with most of them being used by the military for EOD (Explosive Ordinance Disposal) missions or other military-related issues. When referring to a *payload*, payload will be defined by any additional attachment that is not inherently necessary to the locomotion of the platform (i.e. a robotic arm, additional cameras, metal detector). The lead commissioner of *payloadable* robotics has been the defense industry, and while it would be expected that this should inherently lead to the design of versatile and capable platforms, it has had the reverse effect with many robots solving individual problems. With the primary focus being the defense industry, most of these robotic platforms are expensive by nature and not readily available for other applications.

There is, however, a middle class of robotic platforms that try to tackle the diverse needs of the many. The most common of these would either be the QientiQ Talon or the iRobot PackBot. Both of these systems are tracked platforms and both can hold various payloads, with Talon being slow and durable, and PackBot being fast and agile. The goal of these two systems was to have a robust and versatile robot that is capable of urban and rural environments, with the ability to utilize an array of tools to mitigate any situation. While these two systems do accomplish their goals, they also have limitations. Talon, while being able to carry the largest payload, can be unreliable at times. It was the frontrunner of the early era of robotics and has since become outdated. The platform can be bulky, unwieldy, and does not possess any compliant suspension. This can lead to failures when dexterity is needed or when diverse environmental conditions are present. The PackBot is light and agile, but it cannot carry the wide array of payloads that the Talon can, rendering it a major reconnaissance asset but incapable of performing larger tasks. PackBot also does not possess a suspension in the drive train, but rather uses additional articulated arms when trying to climb over obstacles. In comparison to a suspension, this adds more complexity and possible modes of failure.

Design Metrics

When analyzing current platforms, a pattern of unsolved issues can be seen. The existing platforms tend to be overly specialized leading to the necessity of multiple systems which directly leads to an increased cost. Many platforms inherently have a designated forward travel direction, meaning that the platform is built to have advantages only when traveling in the correct direction. This leads to situations when a unidirectional vehicle can be trapped. Terrain is one of the biggest hurdles facing a small platform, which is why many platforms implement tracks. Tracked locomotion gives increased traction while decreasing ground pressure, both very desirable features to have when encountering snow, dirt, or sand. A fixed track drive train can, however, hinder the ability to climb up and over certain obstacles. To combat this, some platforms use arms (e.g. PackBot), while others simply increase the size of the leading wheels. This is effective to a point, but large wheels needlessly increases the size of the platform while articulated arms needlessly increase the electronic and control complexity.

The next critical issue is communications. Most robots are forced to operate under LOS (line of sight) conditions, severely hamstringing their effectiveness when situations involve the labyrinthian characteristics of urban areas. Communication systems that are able to penetrate walls and other non-LOS instances are incredibly expensive and even then there is a limit to how far the signal can penetrate. These high-power radio systems raise cost exponentially and require excessive power from the platform.

Finally, physical size is the last critical factor. This regulates where and for how long the platform can travel, how large of payload it can hold, and how much power is required to perform the task at hand. Size can be a critical factor in determining the overall usefulness of a robot. It must be chosen carefully for a multipurpose platform, as a large variety of tasks must be considered when choosing a size.

From all these considerations, a reasonable set of physical and performance requirements can be determined. The key feature of the rover will be the modular payload system, both the physical attachment system and a universal power / communication interface. To mitigate the terrain concerns, a tracked approach with be used. Unlike its predecessors, this tracked system will be fully suspended and truly ambidextrous. The suspension will allow the platform to traverse step-like obstacles that otherwise would have been insurmountable. A major focus will be on stair climbing, a task that has yet to be perfected by any existing system. This novel design will also allow the platform to enter any situation no matter the environmental concerns and at most have to turn 90 degrees to travel in any direction, opposed to the 180 of conventional systems.

In order to remedy the communication issues, the platform will be able to deploy its own ad-hoc mesh network via disposable Wi-Fi pucks. With the ability to deploy up to 8 pucks that can each have the range of 100 meters of linear distance, over 800 meters can be added to the operators control units range. This greatly increases the distance into an urban environment that communications can be achieved without signal degradation; pucks can be dropped at corners to build an effective line-of-sight chain that allows near-perfect communication throughout a building.

As to the physical size of the platform, in order to perform and urban missions it must be able to travel through the smallest doors and the shortest of ceilings (e.g. air ducts). This necessitates a maximum height of 17.72 inches and max width of 21.65 inches (450 x 550 mm). Typically, the climbing angle of stairs is 34.5 degrees of incline, but most of the existing robot platforms can climb up to 40 degrees. Using this as an objective, the height must be set to at most 15.75 inches (400 mm) to prevent too high of a center of gravity side to side, and a length of at least 30.1 inches (765 mm) to accommodate the max pitch angle of 40 degrees.

Mechanical

Concepts for Action

With terrain adaptability a high-priority goal, an innovative solution of tracked suspension will need to be implemented. Previous generations of tracked platforms have shied away from using suspension to overcome obstacles and have instead used alternative features such as the PackBot arms. This is likely due to the largest concern when deploying a tracked system: the potential to "throw" a track (the track slips off the drive train). This totally cripples the platform unless the user is able to re-engage the tracks, which they are often unable to do remotely. A tracked platform is most susceptible to this action when an axial load is present, such as those caused by point turning (zero-radius turning), or when there is too much slack in the track. A complaint suspension system would generate more slack than a normal style of belt tensioners could take up, allowing this dangerous slack to form. Other systems have attempted to solve this problem by increasing the elasticity of the track; this increases the compliance of the tracks without adding slack and allows for some misalignment without much harm, yet this decreases the power that can be transmitted to the ground and increases rolling resistance of the drive train during all motion.

Suspension Approach

M.A.R.S.U.P.I.A.L. proposes a novel solution to this problem. With an ambidextrous (symmetric front-to-back) design concept, it is possible to use the geometry of the suspension to aid in the tensioning of the track to the point that minimal dedicated tensioners are required. The ambidextrous solution does pose its own problems, however. The primary goal when traversing stairs is to maximize the base line of the vehicle, this makes it easier to accomplish. This means that the system should increase its baseline or at the very least remain constant when traveling over objects. This inherently leads to a system that has a "leading" suspension in the direction of travel; this forces the first contact wheel to move forwards and upwards, over the obstacle. This is considered unnatural and can be inefficient, yet due to the tracked design there is a natural "lead in angle" to this action which will remedy a non-trivial amount of lost effectiveness. However under a cost benefit approach the inefficiency can be sacrificed for the benefits of the increased baseline. To remedy this loss two approaches will be implemented, the first will try to harness the impulse forces generated from the upward travel and attempt to redirect it into a downward force to the second half of the suspension, briefly spiking the available max traction effort into the ground. The latter is the brute force approach, oversizing the motors to accommodate the additional power needed to climb over the obstacles.

Geometric Design and Mathematical Analysis

Current systems that use a similar symmetrical design would be the volute spring style implemented on modern day tanks. This is a leading arm followed by a trailing arm with a spring and damper bridging the gap and connecting them. This allows power to be transmitted through the suspension and increase traction when traveling over objects, when the leading arm is moved upward the trailing arm is pulled downwards. However the relative travel distance of this style of suspension is relatively low, making it unsuitable on its own for the goal of traversing large obstacles. Another common type of tracked suspension is the Christie, developed by J. Walter Christie in the 1940s. This design serves to maximize the suspension travel with a minimal input, working similarly to the human elbow tendons. The M.A.R.S.U.P.I.A.L. platform combines these two styles, and in collaboration the two work in harmony to self-tension the track while also providing sufficient travel. Each arm of the suspension is able to individually travel in excess 100mm vertically; yet compressing the entire system yields a total travel of less than 20mm. Meaning that a dedicated tensioning device should only need to take up 20mm of travel.

The next step is to determine the statics and dynamics of the system; this will yield the necessary lengths and suspension tensions needed in the arms to have equal forces exerted by each of arms (this helps with ground pressure). To keep this system from being statically indeterminate, the equations will be developed by considering the first wheel to be rigid to the ground and the other 3 are only constrained in the vertical axis, like the rollers they represent. Once the system is statically solved the dynamics simulation can begin. The purpose in having a dynamic simulation is to have a rough idea of how the system will react when subjected to external forces. For instance if a large obstacle is hit how will the suspension react and will it recover after the impact or will it reach its static limits and cause a failure?

In order to mathematically solve this problem the suspension must be simplified and broken down into individual components, for this iteration 5 free bodies are identified and used; one representing the 4 arms and the last representing the body of the platform. The next step is to identify the unknowns presented; here there are 28 unknowns, 3 equations per free body yields 15 equations to define the orientation of each, 8 constraints to connect the free bodies and then 5 equations to attach the platform to the ground. A unit step function that will serve as a "down force" to the center of the platforms body will be used to evaluate the motion of the suspension arms. Being a matrix of 28 unknowns this can be very intensive to solve by hand, so a mathematical ODE solver was implemented via computer software to crack the dynamic motion of the system. Proving under expected conditions the suspension will be able to take such a force and rebound to a desired state of equilibrium.

Motor Torque Calculations

The last mechanical issue in need of a mathematical backbone would be the motor torque calculations. This is needed in order to properly choose which motor and gear reduction needed in order to meet the engineering requirements set forth. The assumptions used for these calculations mostly involve the surfaces the robot would ideally come in contact with and the efficiency of the drive trains. When solving for the desired input speed and torque needed by a motor, the end goals must first be found. For this a 45kg robot was used with a worst loading of 70% on a given motor, acceleration forces were taken into account as well as possible incline slopes. The equations used are annotated below.

$$TTE = RR + GR + FA \qquad (1)$$

$$RR = GVW * C_{rr} \qquad (2)$$

Where:

TTE = total tractive effort
RR = force necessary to overcome rolling resistance
GR = force required to climb a grade
FA = force required to accelerate to final velocity

GVW = gross vehicle weight
C_{rr} = surface friction (ground to track friction)

$$GR = GVW * \sin(\alpha) \qquad (3)$$

$$FA = \frac{GVW * V_{max}}{g * t_a} \qquad (4)$$

α = incline angle
V_{max} = max velocity
g = gravity constant
t_a = time to accelerate to max velocity

With a final velocity set in the engineering requirements to be 5 mph (2.2 m/s) and a max incline of 40 degrees as determined by the CG analysis, these metrics will be our worst case scenarios for designing the input. This gave the final output torque required to overcome the worst possible condition the robots could encounter. From here a list of possible gear ratios were evaluated against a known list of existing motors until a reasonable match was found.

Electrical and Software

Pucks

One of the major limitations of existing mobile platforms is the remote control system. Quite simply, if the control signal to a robot it lost, the robot is dead in the water. If the robot is in a hazardous environment, retrieval may be impossible or unsafe. Despite this, most platforms simply use a single radio link for control. The situation can be ameliorated by increasing the radio transmission power, but this can only do so much. In urban environments especially, there are simply too many signal blockers and interference sources (buildings, vehicles, towers, power lines, etc.) to ensure reliable point-to-point radio contact. Technologies like FHSS (frequency hopping spread spectrum) and diversity reception (using multiple antennas and receivers) can help prevent some types of interference, but ultimately a different approach is needed to ensure reliable communication in the RF-hostile environment of a city.

The approach of our platform is a wireless mesh network consisting of small, self-contained radio modules, referred to as “pucks.” These pucks contain a battery, a wireless radio, an antenna, and a control board. In order to reduce costs, off-the-shelf Wi-Fi radios were used for this proof-of-concept prototype. Of course, Wi-Fi is not nearly robust enough for control of mission-critical systems, but it is more than suitable for testing purposes. Each puck’s control board runs Linux, which provides the networking stack and the ability to run the B.A.T.M.A.N. mesh protocol software. Short for Better Approach To Mobile Ad-hoc Networking, B.A.T.M.A.N. allows a mesh network to sit on top of an existing non-mesh network, and requires only the ability to broadcast packets. It can therefore be adapted to any type of wireless communication system that supports packetized broadcasts, and also to certain types of non-wireless communication channels. Like any good mesh network, B.A.T.M.A.N. does not require the network to remain static. All nodes in the network are constantly re-evaluating their neighbor tables, and if a node drops offline or leaves the network, traffic will be routed around it presuming there is another path available. Tests show B.A.T.M.A.N. is able to reroute after a node loss with only a single packet dropped.

In order to build a network where one does not already exist, the robot is outfitted with a payload that can drop pucks on demand. This allows network building to be integrated into the mission; as the robot drives around, either it or its operator can decide to drop a puck to extend the network. If pucks are dropped more regularly than strictly required, the network will contain redundancies that will allow for nodes to drop offline without taking the network down. This is very desirable, especially in a hostile or unknown environment. The nodes have enough battery life to outlast the robot, and can be run over by the robot while in operation without failing. The nodes (in their proof-of-concept configuration) cost less than $100 each, and can thus be abandoned without much financial loss if the mission requires it. Again, if the goal is to keep people out of harm’s way, minimizing the need to recover lost equipment is a very desirable feature.

Control System

The robot is designed all the way through with modularity in mind. Thus, the choice of ROS for the control software was obvious. ROS, short for Robot Operating System, is a highly modular and configurable software framework designed for controlling robotic systems. ROS is used extensively in the commercial robotics world, and thus has a large array of premade software libraries available. This is extremely useful, as it allows many off-the-shelf components to be integrated quickly and painlessly into the robot’s software. Video streaming from the onboard camera was easily achieved, and can be displayed directly in the control software GUI without any modification. Joystick control was added just as easily, with only the glue code to convert joystick inputs to differential drive commands needing to be written.

The control system was centralized around a main computer which was a dual core Intel Atom single board computer.

The modularity of ROS allows payloads to be modular in both a physical and a software sense. ROS provides a unified framework for communicating between segments of ROS software, called ROS nodes. Thus, when a payload is added, its corresponding node can be loaded and immediately integrated into the ROS environment. The puck dropper payload is an excellent example of this. Along with the physical payload, a software node is provided. When the payload is attached and the node loaded, a ROS interface is then presented to allow pucks to be dropped. It simply appears as a new virtual knob, right alongside all the other controls previously exposed. The payload and node can be unloaded just as easily, with all additions / removals being seamless and able to be performed hot (without resetting the software or losing control over the robot).

Power Management

M.A.R.S.U.P.I.A.L. is powered by six military grade lithium ion batteries, each operates at 24 volts (V) nominally and can supply about 10 amps of continuous current. The power management board was developed to centralize the control and distribution of power within the e-box. Not all of the components are suited to operate a 24V so voltage regulators are used to provide 12V, 5V, and 3.3V to all of the essential components of the system. Fuses are used to provide over current protection for sensitive equipment as well as to provide a degree of safety when dealing with such a high density power source.

The power management board includes an onboard Atmega328 microcontroller that is in charge of monitoring real time power characteristics including battery state of charge, instantaneous current usage, and remaining battery life. This offloads the repetitive tasks from the main computer such as reading sensors and real-time data calculations. All data is published to the ROS environment for use by other nodes.

CONCLUSIONS

M.A.R.S.U.P.I.A.L. gives an innovative new spin on the traditional military robot platform. This includes a novel track design that combines the best performance aspects of two widely used suspension designs into one. It also incorporates a new type of radio system which allows the usable range of the robot to be dynamically and intelligently extended as needed. The robot uses industry-standard software to integrate everything in an extensible and modular fashion. Thus, the platform is a good fit for a wide variety of applications, making it a very useful tool for defense and commercial applications.

ACKNOWLEDGMENTS

A special thanks goes out to our sponsor Les Moore and our customer Carnegie Robotics for being a part in making this project a success