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Loper: A Quadruped-Hybrid Stair Climbing Robot

Sam D. Herbert, Andrew Drenner, and Nikolaos Papanikolopoulos
Department of Computer Science and Engineering
University of Minnesota
Minneapolis, MN 55455
{herbert, drenner, npapas}@cs.umn.edu

Abstract— **The purpose of this paper is to describe the Loper, a multi-purpose robotic platform under development at the University of Minnesota's Center for Distributed Robotics. Loper's unique Tri-lobe wheel design and highly compliant chassis make the platform especially suited for overcoming many of the challenges associated with search operations in urban settings. The mechanically simple design and use of commercially available components make Loper easily maintainable. The platform also features long operational time, onboard sensor processing, dedicated motion control, and four reconfigurable sensor bays.**

I. INTRODUCTION

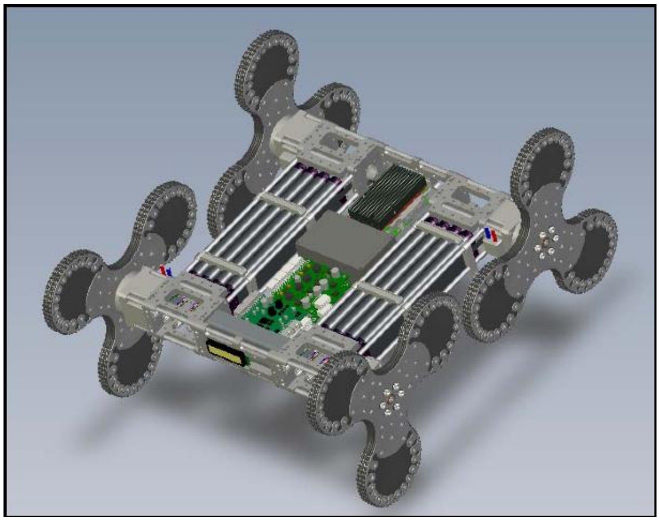

Fig. 1. Loper

In this document we describe the Loper (Fig. 1), a versatile robotics platform capable of operation in a number of environments. A unique combination of Tri-lobe wheels and a highly compliant chassis allow the Loper to easily traverse complex natural and man-made terrains. The hybrid-quadruped design consists of a highly compliant chassis and four Tri-lobe wheels. Each Tri-lobe wheel is coupled directly to a high torque, highly accurate AC servo actuator. The direct coupling of the wheels to the motors creates a mechanically simple and robust system.

The Loper control system is composed of three off-the-shelf components: a dedicated motion controller, a PC-104 form factor computer, and a battery management system. The motion controller and battery management system are monitored and controlled by the PC but are also capable of independent operation. Loper's power subsystem provides significant run time, capable of over 40 minutes of sustained motion or loiter times measured in days to weeks depending on tasking.

Loper is capable of maximum speed on level terrain approaching 8 kilometers per hour and a climbing speed of six steps per second. However, as of this writing the maximum acceptable speed on level terrain is 3.2 kilometers per hour and the climbing speed has been limited to three steps per second with two steps per second used as a cautious climb rate. The maximum expected speed can also be expressed as 4.3 body lengths per second. This is exceptional when compared to other capable stair climbing robot platforms. The current speeds are limited by a number of factors that we are working to understand and overcome.

This paper starts in Section II with a brief look at related works. In Section III the mechanical and electrical design are discussed. Section IV reviews the control strategies utilized for stair climbing, walking, and turning. Section V provides some empirical results based on the implementation of the control strategies described in Section IV. Future work is discussed in Section VI, the conclusion.

II. RELATED WORK

Extensive research has been done in the area of stair climbing for mobile robotics platforms. Humanoid, wheeled, and tracked robots have all been made to climb stairs, however in most of these cases robots where designed for two dimensional operations and then later utilized or modified for stair climbing.

A. Humanoids and Bipeds

Biped robots such as ASIMO [1], [2], BARt-UH [3] and QRIO [4] all demonstrate the capability of biped and humanoid robots for stair climbing. Humanoid and biped robots are generally more expensive and require more sophisticated control systems for control and balance than quadruped, hexapod, wheeled, and tracked robots.

B. Wheeled and Tracked

Wheeled and tracked robots often have problems with stair climbing due to wheel slippage. The Packbot [5], [6] partially overcomes this problem with an additional set of tracks outside of the primary drive tracks. These additional

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tracks can be rotated about the body of the robot to act as legs for climbing. The TAQT robot [7] utilizes two pairs of track-based crawlers which can be swiveled about their geometric centers to climb stairs. This system maintains a low center of gravity when on an incline by shifting the load it is transporting over the outside length of the main chassis. The MSRox system [8] utilizes four "Star-Wheels". Each of the "Star-Wheels" is made of three independent wheels, one mounted at the tip of each spoke and is similar to the Lockheed Tri-Star wheel [9] which served as inspiration for the Tri-lobe wheel employed by the Loper.

C. Others Stair-climbing Methods

Smaller robots can often climb stairs by means of "jumping" from step to step. The Scout [10] uses a small tail normally used for balance to jump autonomously up a flight of steps. Smaller legged robots, such as Mini-Whegs IV [11], can also use jumping as a means of climbing stairs. Jumping, however, is impractical for larger mobile robots due to the power requirements and forces on the robot during the jump and landing.

A number of hybrid robots [11], [12], [13], [14], [15], [16], [17] that combine features of legged locomotion and the simplicity of wheeled platforms have been used for stair climbing. RHex [12], uses six compliant hemispherical wheels to enable easy stair climbing.

III. DESIGN

The goal of this project was to design a robot that could overcome the limitations of urban environments while providing the resources for autonomous or semi-autonomous exploration. This resulted in the Loper, a versatile, robust, and maintainable robotic platform capable of traversing varied terrains. It was decided early in the design process that stairs offered one of the most challenging obstacles to any mobile robot, many of the platform's features such as the Tri-lobe wheels and highly compliant chassis are tailored to the stair climbing task.

At first glance the Loper's Tri-lobe wheels (described in detail in Section III-A.1) are similar in function to the spokes of the "Mini-Whegs" [11]. However, the Tri-lobe wheels are independently driven by separate motors in an active control scheme similar to RHex [12]. This allows the development of multiple gaits that could not be achieved on the "Mini-Whegs" platform. The Loper's Tri-lobe wheels are similar in shape and functionality to the wheels in MSRox [8], however, the Loper's Tri-lobes lack the additional wheel mechanisms in MSRox.

A. Mechanical Design

The primary goal was to build a versatile, rugged, and serviceable platform for operations in demanding urban environments. From the start, it was expected that the platform would suffer a number of tumbles and falls during development, testing, and normal operation. To accommodate this possibility, the chassis and wheels were designed to withstand drops of up to 1.5 meters.

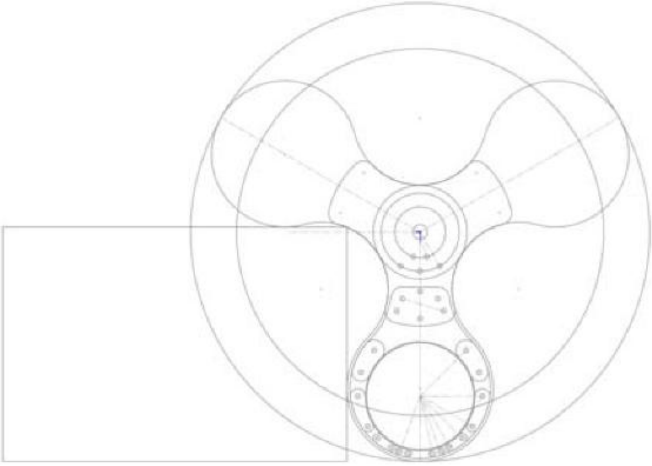

Fig. 2. Tri-Lobe Wheel and a Standard Step

1) Tri-Lobe Wheels:

1) Tri-Lobe Wheels: The Tri-lobe wheels are the most unique design feature of Loper. The wheels were designed to act as a cog when climbing a standard step with a height of 20.32 cm and a landing of 20.48 cm (Fig. 2), allowing the robot to climb steps with exceptional speed. The Tri-lobe wheel is a design inspired by the Lockheed Tri-star wheel [9]. Other early designs that influenced the form of the Tri-lobe wheels include stair climbing hand trucks [18], stepping vehicles [19], and stair climbing vehicles [19], [20]. The Tri-lobe wheels differ from Tri-star wheels in many important ways. The Tri-star wheel features three wheels mounted to a central hub such that two of the attached wheels are normally on the ground. The simplest configuration provides drive power to each of the wheels while allowing the central hub to rotate freely. The free rotation of the central hub allows the Tri-star wheel to rotate over obstacles as much as 75% the height of the whole Tri-star assembly. The mechanically simple Tri-lobe wheels are a modified Tri-star like hub without the attached wheels and sized to the task of stair climbing.

The hub of the Tri-Lobe wheel is sized to prevent the motor housing and chassis from impacting the stair edge when climbing. It has been shown that wheel designs capable of maintaining contact with the stair edge during the climbing activity perform better at the climbing task [12]. The diameter of the lobes and transition angle to the hub was designed to maintain constant contact with the stair landing while climbing.

The shape of the Tri-lobe wheel combines the good contact of the RHex half circle wheel [12] and climbing ability of the Tri-spoke Whegs [13]. In addition to determining the size and shape of the wheel, the stair climbing task also greatly influenced the materials used to construct the wheels.

To provide the needed flexibility and structural integrity the Tri-lobe wheels are constructed using alternating layers of Buna-N rubber and ultra-high molecular weight polyethylene (Fig 3). The polyethylene layers form the support structure for each of the lobes and contain alternating flexures connected by shoulder bolts isolated in rubber tubes. The

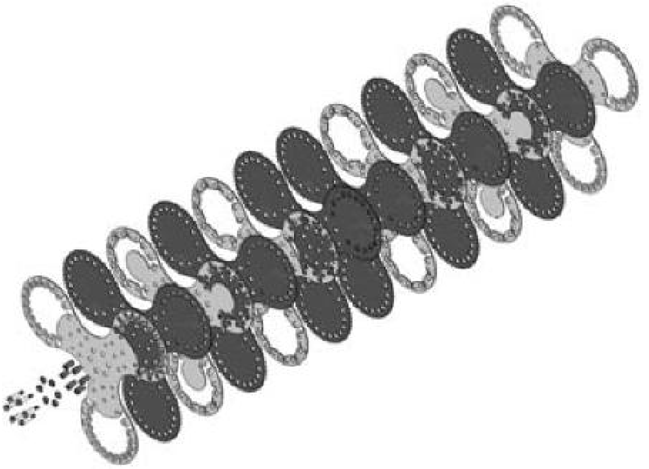

Fig. 3. Tri-Lobe Wheels, exploded diagram

shoulder bolts used to mount the wheel to the motor are also isolated from the structure using rubber tubing. The use of rubber tubes to isolate the wheel layers from the mounting hardware provides additional compliance in the structure and prevents damage to the polyethylene layers. Two of the polyethylene layers also include stiffening tabs to provide lateral support to the structure. The Buna-N layers provide protection to the polyethylene from debris and direct contact with hard surfaces extending slightly beyond the polyethylene layers to provide traction.

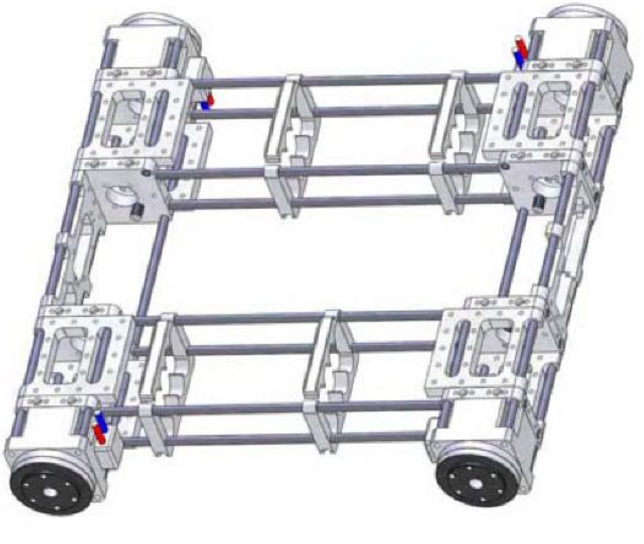

Fig. 4. Loper Chassis

2) Compliant Chassis: The primary support structure for the chassis is the motor housings. Tool steel rods are used to connect the motor housing and polyethylene plates provide mounting structures for electronics and additional plating or skin (Fig. 4).

The electronics are suspended from an aluminum plate in the center of the structure and isolated from shock by rubber bushings at each corner. Lateral motors are connected by three steel rods to allow for twist between the left and right sides of the chassis. The use of the motor housings and steel rods creates a highly compliant structure capable to bending and flexing as needed to keep the Tri-lobe wheels in contact with the ground.

B. Electrical Design

The electrical design is comprised of five major components: a Pentium M computer, motion controller, battery management circuit, eight lithium-ion smart batteries, and four servo actuators.

1) Controls Sub-systems: The controls are divided among three hardware components: a dedicated circuit for battery management, a motion controller, and an on-board Pentium M computer running Debian Linux.

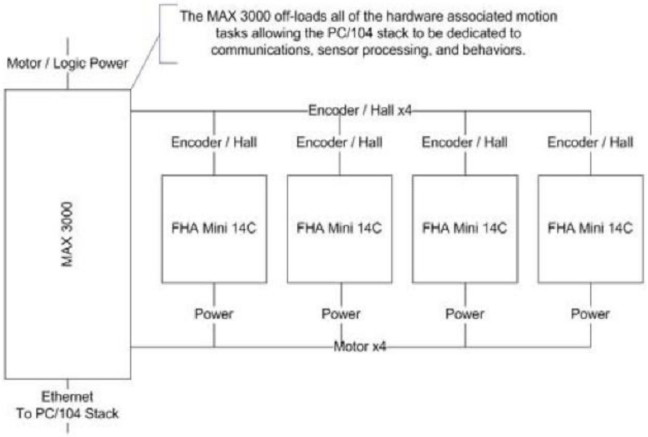

Fig. 5. Motion Controller and Motors

The motion controller (Fig. 5) is capable of driving four stepper, brushed, or brushless motors at 24 volts with a peek current capability of 15 amps. A dedicated digital signal processor on the controller allows many of the motion tasks to be offloaded from the on-board computer, freeing additional resources for higher level control tasks and sensor processing.

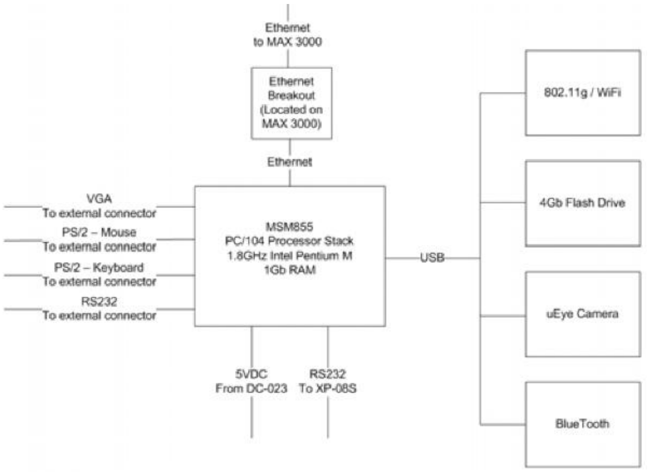

Fig. 6. Computer and Connected Components

The computer (Fig. 6) features Ethernet for communications with the motion controller, IEEE 802.11g (Wi-Fi) and IEEE 802.15.1 (Bluetooth) for external communications. A flash drive is used as the boot device and as a mass storage device for data collection. An effort is underway to standardize all of the platforms in the Distributed Robotics Laboratory to the Player robot server [21], [22]. An installation of Player and the appropriate drivers are in development to make the Loper player-compliant.

The battery management circuit provides the needed power levels to the other sub-systems and provides status information on an external LCD and to the computer through a serial connection. The circuit also balances the load on the lithium ion smart batteries and handles the tasks associated with charging.

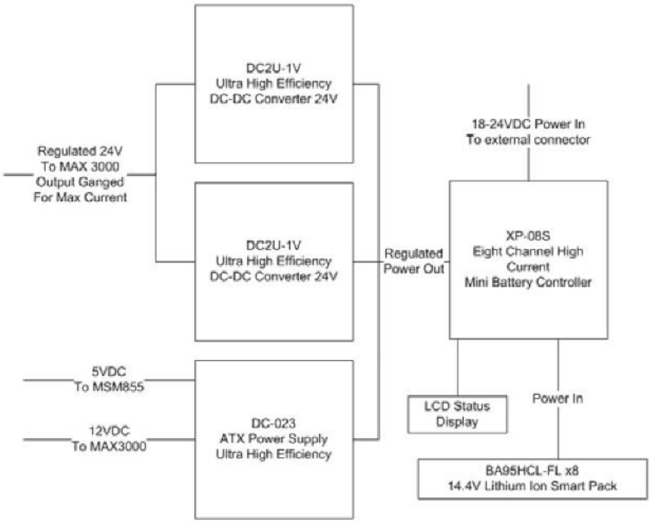

Fig. 7. Power Management System

2) Power Sub-systems: The power sub-system (Fig. 7) consists of eight lithium-ion smart batteries, a management module, and 3.3, 5, 12, and 24 volt DC-to-DC power supplies.

With each motor capable of pulling as much as 15 amps at 24 volts or 360 watts the battery management system needed to be able to handle high current at high discharge rates. The average power consumption during normal walking is approximately 72 watts per motor resulting in 288 watts of continues power draw while moving. Each motor is capable of drawing a peak power of 360 watts for up to two minutes. The 24 volt power subsystem can provide a peak power of 480 watts continuous. The eight lithium-ion smart batteries are rated at 95 watt hours for a total available power of 760 watt hours.

IV. CONTROL STRATEGY

The Loper is a quadruped-hybrid design with legs similar to those described in [11], [12], [13], [14], [15], [16], [17]. Given that Loper is a hybrid platform, the use of activity appropriate gaits and the orientation of the wheels at a given moment are vitally important to optimal performance. Exact positioning of the wheel is handled by the motion controller with encoder feedback at 400000 counts per revolution. Many of the gaits needed for specific motion are also programmed into the motion controller's DSP as described below.

A. Stair Climbing

Climbing requires that the front left and front right wheels remain in phase and that the back left and back right wheels remain in phase; however the phase variation of the front and back wheels is dependent on the period of the stairs. Since the Loper currently lacks sensors capable of determining the optimal phase offset between the front wheels and rear wheels the following strategy has been devised. The platform approaches the stairs with all four wheels in phase, once the climbing activity starts the following error is ignored for the rear wheels and the current is set such that the wheels can only hold position without assistance. The front wheels then pull the platform up the steps and the rear wheels follow as the load decreases and hold position as the load increases. In this manner the phase between the front and rear wheels is allowed to naturally match the period of the steps being climbed. Fig. 8 shows a sequence of images extracted from the first few seconds of a short video of Loper climbing residential stairs.

B. Walking

The ideal walking gait for Loper is a nominal alternating diagonal gait [16] whereby the front left wheel is in phase with the back right and the front right with the back left. Ideally each wheel would be out of contact with the ground for the shortest period of time possible. This requires that the wheels be accelerated when not in contact with the ground and slowed before contacting the ground to match the current desired speed. The Tri-lobe design combined with this gait would only cause the axel to deflect 13% [13] as opposed to 41% when the wheels are in phase. While the nominal alternating diagonal gait has been shown to perform well in open-loop control, the implementation of the closed-loop strategy described above is still under development.

Currently, forward and backward motion is achieved by maintaining a constant phase relationship for all four wheels. It is desirable that all of the wheels are in-phase, so small adjustments are made by the motion controller to maintain this state.

C. Turning

Much like a tracked vehicle, two methods of turning have been implemented on the Loper. The first allows the Loper to turn in place by rotating the wheels at a constant velocity but in opposite direction on the opposite sides of the robot. The second method allows gradual turns while moving forward or backwards by slowing the rotation of the wheels on one side of the Loper.

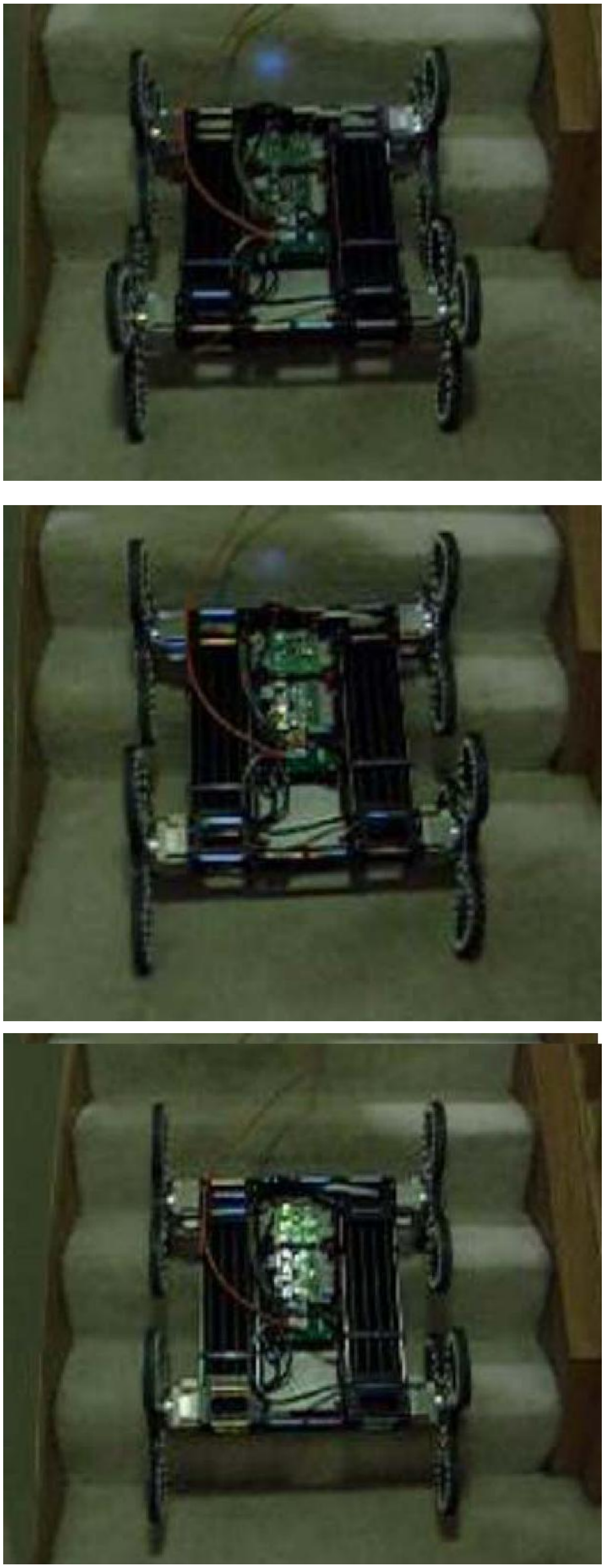

Fig. 8. Loper Climbing Residential Stairs

V. EXPERIMENTAL RESULTS

For this set of experiments the robot was configured to use the on-board motion controller and internal power sources with an external laptop to provide a user interface for the experimenter. Empirical data was collected with regard to the robot's performance at each task.

A. Stair Climbing

Through extensive experimentation it has been shown that the Loper can reliably climb stairs at a rate of two steps per second. Under good conditions, steps with a period close to that of the robot's length and good initial alignment, the Loper easily climbed at a rate of three steps per second. The cog-like nature of the Tri-star wheels provides the platform with a good deal of capability for self alignment with steps. Self alignment was observed with initial alignment errors as high as fifteen degrees from perpendicular.

The two primary modes of failure observed during the stair climbing task where flipping of the robot and jarring such that the robot drove off of the side of the steps. The conditions primarily occurred when the lobe of the front Tri-lobe wheels contacted the step edge rather than the landing. At high speeds, this misstep can result in the robot flipping or slipping sideways on the stairs. Future work will investigate whether the addition of an inertial measurement unit combined with wheel orientation data already present would be sufficient to overcome this failure mode by allowing the controller to compensate before the robot reaches a tipping point during the step.

B. Walking

Experimentation was done with alternating diagonal and in phase gaits. The alternating diagonal gait has been shown to provide stable motion at speeds of up to 88.9 cm or 1.81 body lengths per second. This speed was achieved using open-loop control. The speed was limited by the stress on the motors from the wheel lobes impacting the ground, closed-loop control as described above should overcome this limitation.

Movement with all four wheels in phase has proven to be stable at speeds of not more than 73.6 cm or 1.45 body lengths per second. At greater speeds the simultaneous impact of all four wheels causes a hopping motion and leads to instability in the gait. Further work needs to be done to both stabilize this motion at speeds greater than those listed and take advantage of the hopping behavior noted.

VI. CONCLUSION

The Loper is a hybrid robot designed to overcome stairs, steps, and other obstacles in urban environments where wheeled and tracked robots are known to have difficulties. With its mechanical simplicity and long battery life, the Loper has the potential for autonomous operation over long periods of time. The challenge we now face is to devote the time and vision needed to fully realize this platform's potential. The paper will conclude with a brief overview of future work related to the Loper.

A. Sinusoidal Motion

As mentioned in Sections III and IV the Loper is currently using a basic motion profile with constant velocity and or torque. As mentioned in Section III the implementation of a gait that minimized the time a lobe was not in contact with the ground during a walking gait would greatly improve the robots performance. Motion of this type would require that the motion controller predict when a lobe has lost contact with a surface. Such a predictive algorithm should be conceivable given the torque, following error, and position data available in the motion controller. Once contact with a surface is lost the motion controller would use a sinusoidal acceleration profile to reach some maximum velocity or middle position between lobs. The opposite acceleration profile would then be used to return the wheel to the proper forward velocity before the lobe contacts the surface. Motion of this type would improve the speed of the Loper without increasing the instability of motion.

B. Internal Sensor Additions

Pose estimation is a possible area of exploration for improving the climbing ability of the Loper. One possible solution is the use of inertial monitoring units to estimate if a wheel is in contact with a stair landing or edge. Due to the compliant nature of the Loper chassis and wheels modeling and experimentation will be needed to determine if a single IMU centrally located on the chassis or four IMUs located one at each motor will be needed. The data from the IMUs can most likely be feed directly to the motion controller allowing rapid response to situations that could result in wheel slip or the robot tipping.

VII. ACKNOWLEDGEMENTS

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