Switchblade: An Agile Treaded Rover

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***Abstract*—A versatile unmanned ground vehicle (UGV) should be able to traverse rough terrain while retaining a small form factor for navigating confined spaces. Such a vehicle, dubbed Switchblade, is developed in the present work via an effective combination of a novel transforming mechanical design, capable onboard electronics, and advanced feedback control algorithms. A single chassis holds the actuators, sensors, electronics, and battery. Shafts protruding from either side of this chassis connect to tread assemblies. Rotation of this shaft causes the treads to advance for translational movement; rotation about this shaft causes the entire tread assembly to rotate with respect to the chassis. Vehicle orientation is estimated via onboard filtering of optical encoders and MEMS accelerometers and gyros. In its horizontal configuration, Switchblade operates as a differential-drive treaded platform. In its various upright configurations, Switchblade operates as a mobile inverted pendulum, capable of surmounting obstacles, including stairs, that would otherwise be impassable by a vehicle of its size. Design-for-manufacturing (DFM) and design-for-assembly (DFA) techniques are employed to reduce cost, part count, complexity, and assembly time without sacrificing system capabilities. The resulting platform is well suited for a variety of socially-relevant applications, including reconnaissance, mine exploration, and search & rescue.**

I. INTRODUCTION

INVERTED pendula are often used in controls labs as a fundamental teaching tool. In recent years, mobile inverted pendula have become increasingly popular, including the Segway Personal Transporter [1]. The Segway is perhaps the only mobile inverted pendulum to have yet ventured outside of the sheltered lab environment on a large scale, and is itself largely operated on flat sidewalks. A number of applications motivate small, simple UGVs that can robustly overcome complex terrain challenges, while also being able to navigate in confined spaces; such applications include patrol, search & rescue, mine exploration, and the disposal of improvised explosive devices (IEDs). In such applications, it is generally advantageous for the vehicles used to be inexpensive, so that multiple vehicles may be deployed to accomplish a given mission, and the loss of some is acceptable. The cost of a UGV may be reduced by minimizing its size and mechanical complexity, noting that advanced feedback control algorithms, once designed, may generally be implemented at very low cost.

We begin by reviewing existing mobile inverted pendula. The most common paradigm today is a two-wheeled platform [2], with steering accomplished by differential drive. Another class of mobile inverted pendula uses a single ball instead of two wheels, thereby achieving holonomic locomotion [3], [4].

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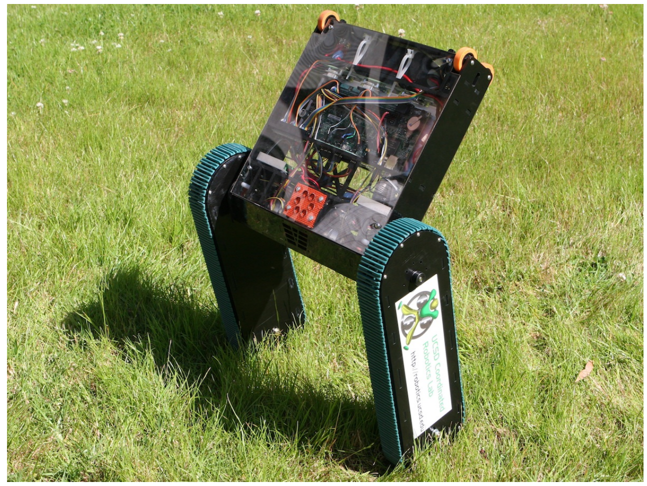


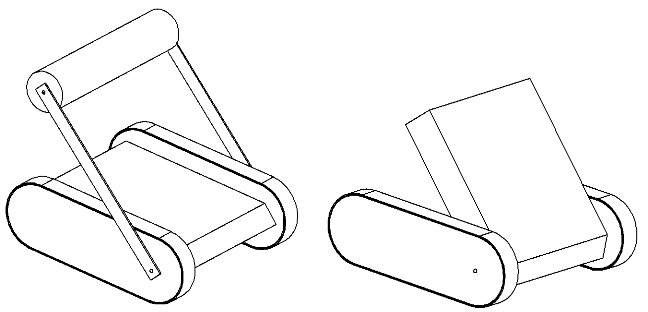
Fig. 1: Completed Switchblade v.2 prototype.

Both designs have a fundamental weakness in common: the maximum obstacle size that such a vehicle can overcome is limited by the diameter of its wheels or ball.

Legged robots often use a linear inverted pendulum model and calculations of the zero moment point to maintain balance while stationary or moving [5]. Such robots have a great deal of flexibility when overcoming obstacles: they may step over or onto an obstacle [6], or even hop over an obstacle [7]; however, they are also mechanically complex, with many actuators and possible failure points.

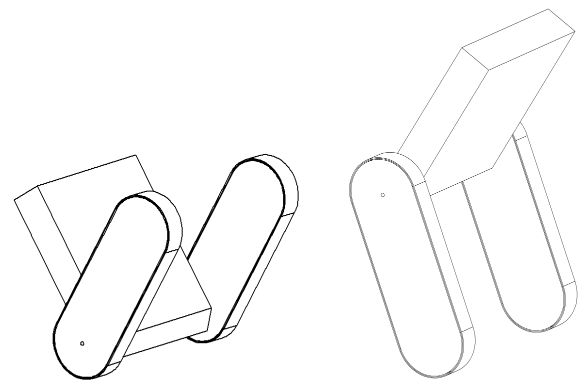
The standard treaded platform (manned versions of which were developed by the British in WW1, and smaller unmanned versions of which were developed by the Germans in WW2) consists of two fixed tread mechanisms mounted on opposite sides of a central chassis. This type of UGV performs well over a variety of both smooth and rough terrain (including loose dirt and gravel, sand, snow, mud, etc.), but cannot overcome obstacles larger than the diameter of its tread sprocket. This limitation may be extended by adding additional idler sprockets to increase the height of the tread assembly (such as the trapezoidal shape of the treads of an M1 Abrams tank), or by adding secondary articulated treaded segments or "flippers" (e.g., the iRobot PackBot [8]). Additional treaded segments may be added to increase a treaded vehicle's agility [9], but at the expense of significantly increased cost, complexity, and possible failure points; for instance, a serpentine robot may consist entirely of treaded segments [10].

Another notable treaded platform is the Vecna Robotics Battlefield Extraction-Assist Robot (BEAR; see [11]), which has two-segment tread assemblies pivotally attached to either side of a central torso which also has two manipulator arms.



(a) v.1: Rotatable boom arm. (b) v.2: Independently-rotatable tread assemblies.

Fig. 2: Two generations of the Switchblade design.



(a) V-balance mode. (b) C-balance mode.

Fig. 3: Fundamental Switchblade balancing modes.

The BEAR can operate with its articulated tread assemblies in a number of different configurations, including dynamically balancing on either end of the tread assemblies with inverted pendulum control. Note that the BEAR is a large, complex vehicle, with tread segments large enough to overcome many common obstacles (stairs, medium-sized rubble, etc.) without utilizing balancing behavior.

In this paper, we describe a compact treaded UGV, dubbed Switchblade, which is capable of overcoming obstacles nearly as high as its treads are long via a unique mechanical architecture and clever implementation of robust feedback control algorithms (Fig. 1). We first discuss the design evolution of the platform and some of the quasistatic and dynamic maneuvers of which this platform is capable. Next, we describe the current prototype in detail and conclude with the future work for this platform.

II. Design Evolution

We have experimented with two different mechanical architectures which facilitate a variable center of mass. The v.1 design has a boom arm which can continuously rotate about the idler sprocket axle of the treaded chassis (Fig. 2a). The end of the boom arm contains a substantial counterweight (the battery), such that pivoting the boom arm significantly moves the center of mass. The v.2 design instead has independent tread assemblies which can rotate continuously about the main drive axle of the chassis (Fig. 2b). Changing the angle between the chassis and tread assemblies moves the center of mass. There are no physical connections between the two tread assemblies to keep the two parallel, but feedback control may be applied when it is desired to keep the two tread assemblies in line.

Unlike the canonical inverted pendulum, the unstable equilibrium point (the angle of the chassis with respect to gravity) is not constant and instead depends on the angle of the boom arm or tread assemblies with respect to the chassis, and their relative mass distributions. The angle of the chassis with respect to gravity that positions the center of mass over the contact point with the ground can be calculated with the known properties of the vehicle.

Both designs can operate in a horizontal configuration (Fig. 2) in which the robot functions much like any other treaded skid-steer robot, with the ability to independently drive each tread forward or backward to drive and turn. The treads act to minimize contact force on loose surfaces and maintain traction better than wheels. Note that the actuated tread assemblies of the v.2 design and boom arm of the v.1 design make the robot impervious to high-centering. Note also that both designs operate just as easily "upside-down" as "right side-up."

The maximum obstacle size that either design can overcome is related to its overall height. When the vehicle is horizontal, its height is the diameter of the tread sprocket; when the vehicle is upright, its height is related to the tread length. The total height of the vehicle is thus variable over a large range, and can be adjusted as necessary: the robot can upright itself to overcome large obstacles, then lay itself back down to, e.g., pass freely underneath parked cars.

To overcome an obstacle larger than the sprocket diameter, the vehicle approaches the obstacle while balancing upright, "leans" onto the obstacle by shifting its center of mass over the point of contact with the obstacle, then drives over the obstacle. An alternative maneuver to climb stairs uses the non-treaded section of the robot (either the boom arm of v.1 or chassis of v.2) as a lever. The robot approaches the step in a horizontal configuration, and rotates the non-treaded section against the step; leveraging against this contact point appropriately while driving the treads, the center of mass may be pushed on top of the step. The rest of the vehicle may then be rotated up onto the step. After these moves, the robot is backwards relative to how it approached the stair; to climb further stairs, the robot must reorient itself. If the length of the robot is less than the length of the stair, the robot can flip itself in place on the stair. The entire sequence can be repeated to climb multiple stairs.

Both designs may balance on either end of the treads by taking advantage of the tread transferring torque to the idler sprocket. In a wheeled design, the idler wheel would be passive unless a second motor was driving it or if a chain

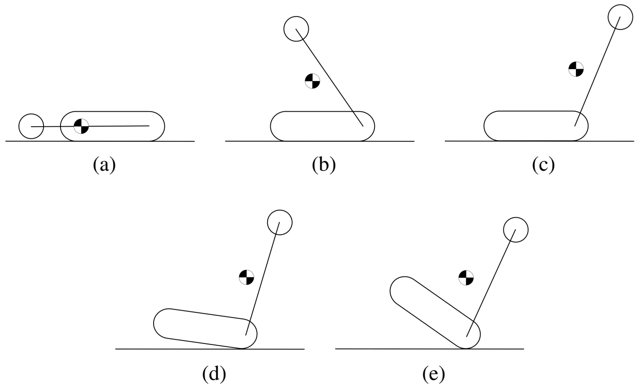


Fig. 4: Quasistatic maneuver for uprighting into V-balance mode with the v.1 design.

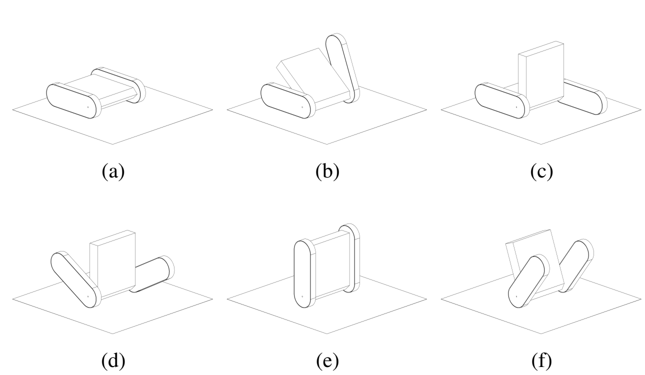


Fig. 5: Alternative quasistatic maneuver for uprighting into V-balance mode enabled by the v.2 design.

or belt connected the front and rear wheels. When the robot is balancing on the sprockets coaxial with the pivoting axis, a side view of the robot resembles the letter "V" (Fig. 3a), this maneuver is referred to as V-balance mode. Alternatively, the robot may balance on the distal sprockets of the treads, a side view of which resembles a crude version of the letter "C" (Fig. 3b), this is called C-balance mode. By driving the treads, rotating the angle of the boom arm or tread assemblies, or actuating both simultaneously, the robot is able to maintain its balance.

The maximum height of the robot in V-balance mode is the length of the treads with the center of mass approximately central, whereas in C-balance mode the maximum height is the length of the chassis plus the length of the boom arm or tread assemblies minus the radius of the sprocket, with the center of mass above the treads. The added height in C-balance mode allows the robot to stand up taller, climb higher obstacles, and an onboard camera to see farther. The ground clearance of the v.2 chassis can be nearly the length of the tread assemblies, allowing the robot to pass over minor obstacles.

The range of actuation of the boom arm or tread assemblies while in V-balance mode is dependent on the mass properties of these components and the chassis. The boom arm of the v.1 design is longer than the chassis, such that while in C-balance mode, the boom arm has a finite rotation range without contacting the ground. The tread assemblies of the v.2 design are longer than the chassis, such that the chassis may rotate continuously and pass through the tread assemblies while in C-balance mode. To transition from V-balance mode to C-balance mode and vice versa, the robot must first transform into its horizontal configuration. The motion sequences for both designs to transition from horizontal to these balancing maneuvers are discussed next.

A. *Uprighting into V-balance mode*

In the v.1 design, starting from a horizontal configuration, the boom arm is rotated up and out until the center of mass is directly over the sprocket of the pivot axis (Fig. 4a - Fig. 4c). By driving the treads and actuating the angle of the boom arm simultaneously, the angle of the chassis can be changed quasistatically without changing the horizontal position of the center of mass (Fig. 4d - Fig. 4e). This process is reversible and can be used to transform back into a horizontal configuration.

Another quasistatic, reversible uprighting maneuver is possible with the v.2 design (Fig. 5). From a horizontal configuration, one tread assembly is rotated 180 degrees and the chassis is rotated 90 degrees until vertical (Fig. 5a - Fig. 5c). Both tread assemblies are then simultaneously rotated up and towards the chassis and the balancing controller is switched on with a vertical reference command (Fig. 5d). Once the tread assemblies are in line with the chassis (Fig. 5e), they may be rotated to an arbitrary angle (Fig. 5f).

B. *Uprighting into C-balance mode*

To transition the v.1 design from horizontal to C-balance mode, we implemented a bang-bang controller (Fig. 6). The boom arm is rotated back and forth near the resonant frequency of the structure to create a rocking motion between the ends of the treads (Fig. 6b - Fig. 6e). Once the robot is momentarily up on the rear end of the treads, the bang-bang controller is turned off and the balancing controller is turned on (Fig. 6f). At this point, the boom arm can be rotated to an arbitrary angle, including vertical. If, while balancing upright, the robot experiences a large enough disturbance to knock it down, the robot can re-upright itself using the same procedure.

This dynamic uprighting maneuver is not ideal as it requires high instantaneous torque loads from the motors. This maneuver also requires more energy for the v.2 design because the tread assemblies are longer than the chassis. A quasistatic method to transform from horizontal to C-balance mode is possible with the v.2 design (Fig. 7). First, the robot lifts itself into an "A" shape by synchronously rotating the tread assemblies out and pushing them against the ground until the rear panel of the chassis is parallel to, and in contact with, the ground (Fig. 7a - Fig. 7g). One of the tread assemblies is then rotated up and over the top of the chassis until it makes contact with the ground on the opposite side of the robot (Fig. 7h - Fig. 7j). Then both of the tread assemblies are simultaneously rotated towards the chassis until parallel in concert with the

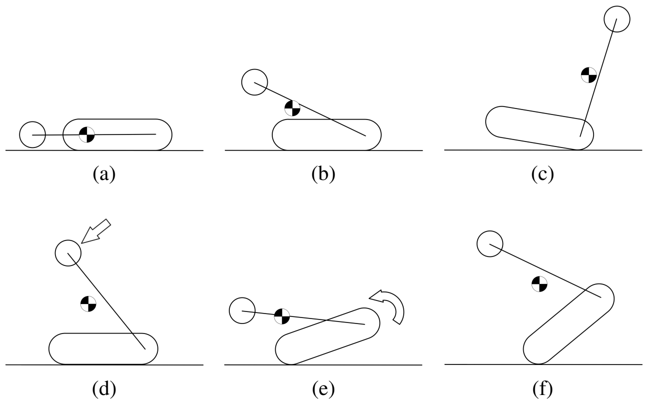


Fig. 6: Dynamic maneuver for uprighting into C-balance mode with the v.1 design. Arrows indicate the dynamic part of the maneuver.

treads rotating to keep the center of mass constant (Fig. 7k). This action lifts the rear of the chassis off the ground and the robot is now in C-balance mode. The chassis may be rotated to any arbitrary angle while maintaining balance (Fig. 7l - Fig. 7n). This sequence of moves can be reversed to transition back to horizontal, unlike the v.1 maneuver.

III. Advanced Maneuvers

A. Chasm Crossing

Using the independent nature of the tread assemblies in the v.2 design, the robot may drive over a chasm or ditch nearly as wide as the tread assembly is long. The tread assemblies are rotated 180 apart and the chassis is positioned vertically, such that the center of mass is centered above the main drive axle (Fig. 8a). Balancing over a chasm is another unstable equilibrium, dynamic stabilization about the roll axis is accomplished by pivoting the tread assemblies to tilt the chassis side-to-side.

B. Active Suspension

Driving over rough terrain may induce unwanted vibration in the boom arm of the v.1 design or the chassis of the v.2 design, this vibration can be reduced by pivoting the boom arm or chassis, respectively, in response to a disturbance. Given the nature of the coupled system, the greatest disturbance rejection is realizable at the end of the boom arm or chassis, farthest from the pivoting axis. One application of such an active suspension system is image-stabilization for a camera mounted in or on the boom arm or chassis.

C. Perching

A particularly advanced, and challenging, maneuver for either design is balancing on an edge, such as the end of a stair (Fig. 8b). Maintaining traction is critical, the material and shape of the treads and edge determine the critical slip angle. The contact angle can be controlled to a value less than this. Ultimately, the robot may drive up a stair, contacting only the edge, while pivoting the boom arm or chassis to keep the center of mass directly over the edge. This maneuver may be repeated up a staircase depending on the rise and pitch angle of the stairs, the length of the treads, and the critical slip angle.

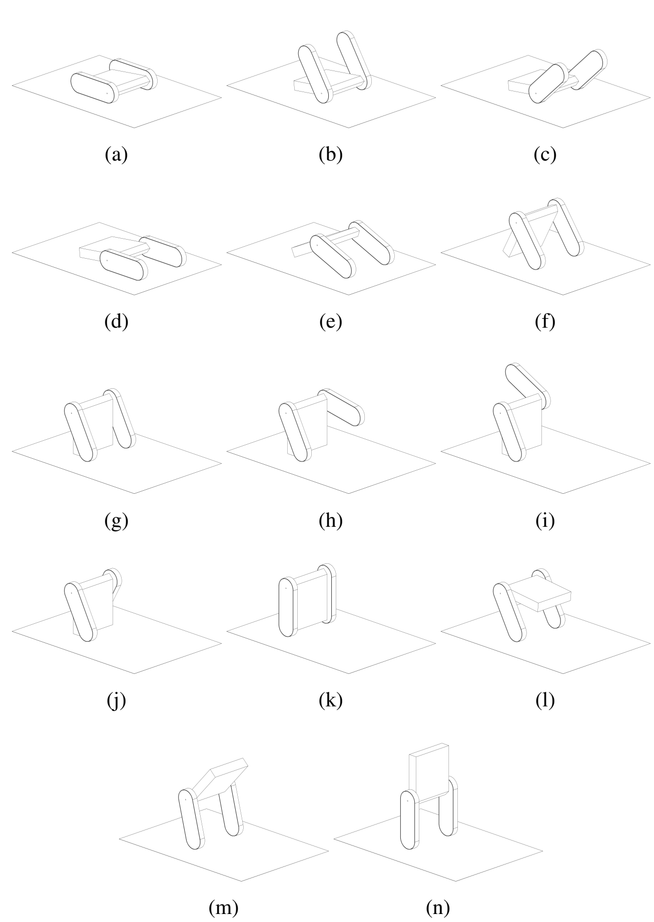


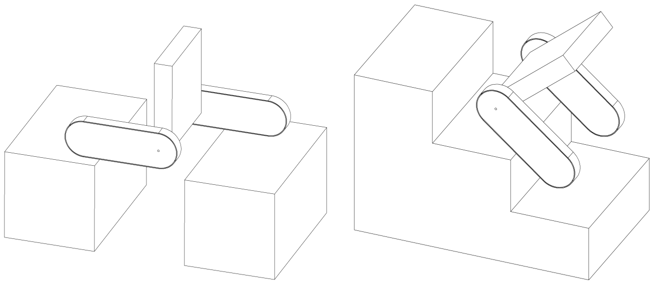
Fig. 7: Quasistatic maneuver for uprighting into C-balance mode enabled by the v.2 design.

IV. Current Prototype

After some experience with a v.1 prototype, we decided to implement the v.2 design to enable additional maneuvers. The design goals of the prototype included performance goals (speed, ground clearance, etc.) as well as manufacturability goals (cost, ease of manufacture, etc.).

A. Mechanical Design

The metaphorical keystone of this design is the hip joint that pivotally connects each tread assembly to the chassis of the robot. A novel, patent-pending two degree of freedom joint is introduced to connect the chassis to each tread assembly (Fig. 9). The joint combines the axis of rotation of the tread assembly with respect to the chassis and the axis of rotation of the sprocket driving the treads into one stainless steel shaft. The shaft rides in ball bearings in both the chassis and tread assembly. The end of the shaft inside the chassis is directly coupled to the output shaft of the planetary gearbox motor. The other end of the shaft passes through, and spins freely



(a) Chasm crossing. (b) Perching on the edge of a stair.

Fig. 8: Advanced maneuvers.

relative to, a large spur gear which is rigidly mounted to the tread assembly and the shaft is finally rigidly coupled to the tread drive sprocket. A second stainless steel shaft is mounted inside the chassis parallel to the first. A pinion gear, mounted on the end of the second shaft that extends from the chassis, drives the large spur gear, and hence the rotation of the tread assembly with respect to the chassis. The other end of the second shaft is directly coupled to the output shaft of a smaller planetary gearbox motor with a much higher gear reduction.

With both motors mounted in the chassis, this joint independently transmits two coaxial torques, one to rotate the sprocket driving the treads and a second to rotate the tread assembly with respect to the chassis. Optical encoders are mounted within the chassis coaxially on both shafts. The actuation of the two degrees of freedom on each hip joint enable the robot to perform its unique suite of maneuvers. A set of passive, un-actuated wheels are mounted on the end of the chassis opposite the main drive axles. The wheels prevent the chassis from dragging on the ground when the tread assemblies are rotated higher than the chassis.

The design of the hip joint keeps the motors and sensors within the chassis, which greatly simplifies wiring by eliminating the need for slip rings about the main drive axle. However, it may still be useful to place sensors or other electrical components in the tread assembly. Space was purposefully left in between the tread assembly and the chassis along the main drive axle for a four channel slip ring.

The diameter of the sprocket was chosen to give greater than 25 mm of ground clearance for the chassis when in a horizontal configuration and in conjunction with the motor and gearbox choice to have sufficient torque to lift the weight of the robot and a top speed in excess of 2.5 m/s (6 body lengths per second). The traction between the treads and various ground surfaces is balanced between the need to grip while accelerating and the need to slip while skid-steering. It is particularly critical to maintain traction while balancing upright, where a tread slipping may cause the robot to fall. The off-the-shelf treads are made of acetal and may be modified by applying a rubberizing coating or adding grousers to increase traction. The treads are continuously supported underneath, any large normal force on the treads will be transferred to the structure of the tread assembly (also acetal) without adding

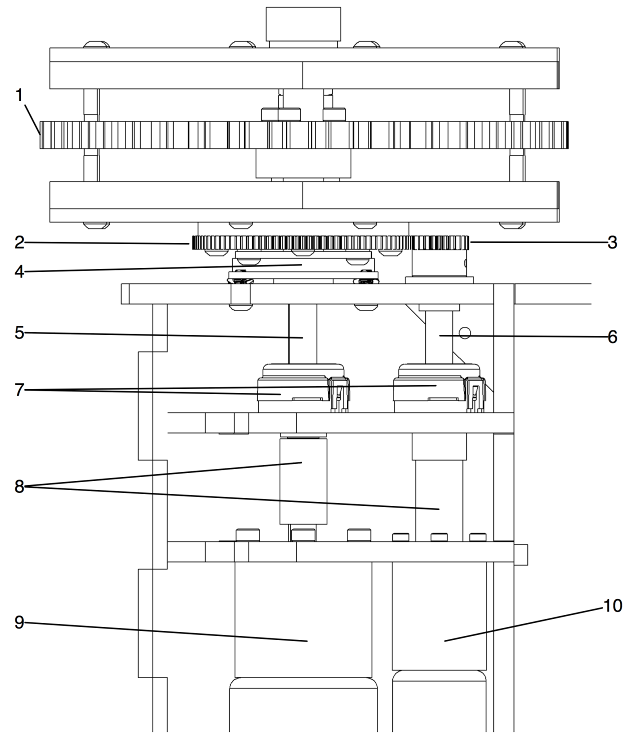


Fig. 9: 2 Degree of freedom hip joint of the v.2 Switchblade: (1) tread sprocket, (2) spur gear, (3) pinion gear, (4) optional slip ring, (5) main drive axle, (6) rotation axle, (7) optical encoders, (8) shaft couplers, (9) tread motor, and (10) rotation motor.

significant resistance to driving the treads because of the low coefficient of friction of the acetal-acetal contact. The position of the rear idler sprocket is adjustable to vary the tension of the treads.

Great pains were taken to minimize the part count, particularly the custom part count, and to reduce the number of machining operations per custom part. Off-the-shelf parts were used wherever possible to reduce manufacturing time. All but two of the custom parts are laser-cut from sheets of acetal, with thread-tapping of some holes (thus avoiding the need for nuts) and press-fitting bearings being the only secondary machining operations. The symmetry of the design reduces the unique part count and many parts are orientation-agnostic, simplifying assembly. Those parts with an orientation dependence are automatically marked with identifiers (arrows, etc.) by the same laser-cutting machine used to cut the pieces from stock material. The remaining two custom parts are formed from stainless steel rod stock with simple operations on a lathe and milling machine. The 26 unique custom parts account for 73 pieces used in the assembly of each robot, most parts being used multiple times by various symmetries.

The design process included careful consideration of assembly time. The parts of the superstructure are quickly assembled with a series of interlocking tabs and slots (Fig. 10), thereby minimizing the number of mechanical fasteners needed and

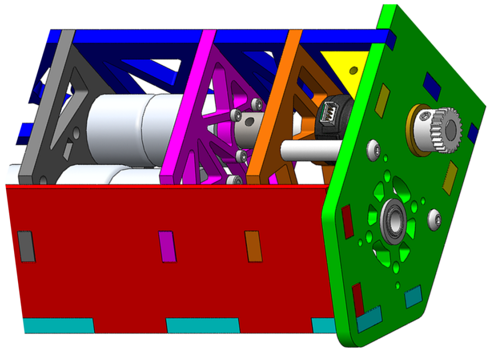


Fig. 10: Tab-and-slot construction simplifies assembly and reduces the number of screws required.

saving cost, weight, and assembly time. A team of five undergraduates working with the lead author were able to construct 12 robots from part manufacturing to final assembly in 10 weeks.

B. Electronics

Switchblade is built around the National Instruments sbRIO 9602 control board. This board has both FPGA and PowerPC processors, which gives flexibility in handling both low-level high-speed tasks and more complex control algorithms, and is programmed using both the LabVIEW Control Design and Simulation Module and the LabVIEW Robotics Module. Onboard ethernet coupled with a wireless ethernet adapter enables real-time wireless communication, debugging, and deployment of software. A 16-bit analog to digital converter reads the output of the analog sensors and monitors the battery voltage. A 6-DOF inertial measurement unit is mounted in the center of the chassis, using low-cost MEMS analog sensors: a three-axis accelerometer, a single-axis gyroscope, and a dual-axis gyroscope (mounted to measure orthogonal axes). Optical quadrature encoders mounted on each of the motor shafts are used to measure the angles between the chassis and each tread assembly, the speed of the relative rotation, as well as the position and velocity of the tread movement. These proprioceptive and exteroceptive sensors enable the robot to estimate its position and orientation. An onboard lookup table maps the angle of the tread assemblies to the reference angle of the chassis with respect to gravity that will position the center of mass over the contact point. Different tables are used for each balancing maneuver.

For simplicity, a single, high-capacity battery powers both the electronics and all the motors. A lithium polymer battery is used because of the excellent energy density (by both mass and volume). The battery is placed at the rear end of the chassis to increase the rotational inertia of the chassis about the main drive axle. A color CMOS camera outputs an analog signal to a dedicated daughter card, the MoviMED AF-1501c frame grabber. Images can be processed onboard or sent back to a computer for further processing or teleoperation. The reconfigurability of the robot itself allows the camera to be pointed without additional actuators: panning the camera is achieved by simply turning the robot and the tilt of the camera is determined by the angle of the chassis, which can be freely adjusted while either horizontal or balancing upright. Off-the-shelf motor drivers convert a low-power digital signal from the control board to a 32 kHz PWM signal to drive each motor.

V. Conclusions

A novel robotic platform has been presented which combines the treads of a tank with the balancing behavior of an inverted pendulum to reach a new level of agility. The robot can overcome obstacles on the order of the length of the robot instead of the order of its height. A two degree of freedom hip joint enables the current prototype to perform complicated maneuvers with relatively simple internal structure and wiring. This platform has potential for applications in search and rescue, mine exploration, homeland security, border patrol, reconnaissance, and ordnance disposal.

Future work for this platform includes improving the performance of the balancing controllers and adding programming to switch seamlessly between different modes of operation, including gracefully recovering from falls. The control systems implemented will be presented in a future paper. Integrating vision algorithms will enable obstacle detection, namely stairs, improving the situational awareness of the robot. The final goal is being able to automatically transform to the appropriate configuration based on the terrain encountered.

Acknowledgments

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