A WHEGS ROBOT FEATURING A
PASSIVELY COMPLIANT, ACTIVELY CONTROLLED
BODY JOINT

by

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For My Grandparents:

Rosie, Evelyn, Richard and Ben
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A Whegs Robot Featuring A
Passively Compliant, Actively Controlled Body Joint

Abstract

by

ALEXANDER BOXERBAUM

In this work, I present the next generation of Whegs™ robots, DAGSI Whegs™, which has been completed and extensively field-tested (Figure 1). Several innovations have made this robot more rugged and well suited to autonomous operation than previous designs. Specifically, an actively controlled, passively compliant body joint has been designed and tested. To date, it is the only Whegs body joint to have never failed. The chassis is a structural box design, which is both water and dirt resistant, and provides a flexible mounting system for electronics. New designs of the wheel-legs, torsion devices and steering mechanisms have also been developed and tested. Two large payload spaces have been created by moving the drive chains to the interior sides of the chassis, and the torsion devices to the outside. A two-dimensional dynamic simulation of the robot has also been constructed, and has been used to study the effects of weight distribution on obstacle climbing and to investigate future autonomous climbing strategies. Moving the center of mass forward allows the robot to climb taller obstacles. Using a weight distribution optimized using simulation, DAGSI Whegs™ can climb step shaped obstacles as tall as 2.19 times the length of a leg. Results from field testing show that the robot has good climbing capabilities in rugged unstructured terrain.
1. INTRODUCTION

1.1 BIOLOGICAL INSPIRATION AND ADVANCED MOBILITY

If robots are to become a part of our daily lives, or perform tasks that are dangerous for humans to do, they must learn to navigate the unpredictable, rugged terrain that we overcome with relative ease. Of the many methodologies attempting to solve this problem, one that takes inspiration from biological examples makes good sense. Animals are remarkably good at a myriad of tasks that humans can only dream of accomplishing. If we could create a robot that climbs half as well as a cockroach, we would be doing at least twice as well with robots as we are now.
This basic justification for biologically inspired robotics has a few caveats. The highest level goals are bound to be different. Whereas a cockroach has evolved into a creature who’s main function can be seen as passing on its DNA (via finding a mate, locomoting, harvesting food and not getting killed), we may wish to design a robot that has a far more specific aim, such as harvesting crops or saving people from collapsed buildings. To that end, this robot would probably not need a reproductive system.

The other major qualifier is that we have a very limited palette to work with, both in terms of materials and construction methods. All complex biological systems grow out of a single celled embryo to form structures at virtually any scale. Whereas we are just now learning to create devices on the micro and nano scale (often using biological mechanisms such as artificial DNA), biological systems have no such scale limitation. DNA is made up of molecules on the nano-scale, and this DNA codes for proteins of the same size. Thus, virtually all the wonderful systems our body uses to locomote such as bone, muscle, circulatory systems and neurological circuits take advantage of systems that are extremely small and therefore are excruciatingly hard to match in quality. Thus, we have to make do with some very crude substitutes, such as motors, integrated circuits and aluminum.

Nonetheless, there is much to gain by studying biological systems. Work done at this lab and many others have led to significant advances in the field of biorobotics. Robots have thus far had limited success navigating truly rugged and unstructured environments, as well as reliably completing such simple tasks as walking on a side walk and up a flight of stairs. Improvements in locomotion ability would allow robots to do
tasks such as mine clearing, terrain mapping, geological exploration and data collecting, and search and rescue operations inside collapsed buildings or mines.

1.2 THE WHEGS CONCEPT

Accurate reproductions of various biological systems such as artificial muscles, and systems with a large number of degrees of freedom are very difficult to construct and control. These systems such as Robot III and Robot V are very useful in studying the control problem, and even how cockroaches walk (Fig 2) (Nelson, 1997). However, due to their high complexity, they are currently limited to the laboratory setting. Nonetheless, abstracted biological principles may be still applied to methods of locomotion with results that are efficient, effective and elegant.

Figure 2: Robot III and Robot V, platforms with a large number of degrees of freedom and cockroach inspired kinematics.

The Biorobotics Lab has developed a hybrid wheel-legged platform, dubbed Whegs (Allen) This concept vehicle draws inspiration from cockroach mobility principles, and implements these principles into the mechanical design in a way such that high-level control of low level function is not necessary. Most Whegs robots only contain a single
drive motor that powers four to six multi-spoked appendages called wheel-legs (Figure 3). Neighboring legs are often offset by 60° yielding a tripod gait. The wheel-legs allow the robots to climb over larger obstacles than a vehicle with similarly sized wheels. Whegs robots have compliant mechanisms in all of their axles, which we refer to as “torsionally compliant devices,” or ‘torsion devices. These mechanisms allow the wheel-legs to passively adapt their nominal tripod gait to irregular terrain (Figure 4) (Ritzmann, 2004). Additionally, the lab has developed robots incorporating a body flexion joint (Allen) (Dunker, 2009). This actively controlled joint enables it to model cockroach behavior – extending to reach its legs higher preceding a climb and flexing to avoid high centering, thereby improving its climbing ability (Figure 5). These robotic platforms have successfully navigated complex and varied terrain under both full (Figure 6) (Horchler) and partial autonomy (Figure 7) (Lewinger, 2005, 2006).
Figure 3: Many examples of wheel-legs from Whegs robots.

Figure 4: Cockroach gait and obstacle climbing with (A) and without a bodyjoint (B).
Figure 5: Whegs II using its body joint to prevent high-centering.

Figure 6: Agri Whegs under autonomous navigation in a beach environment.
1.3 **Robots with Reduced Actuation That Predate Whegs**

Recent predecessors to Whegs include PROLERO (Figure 8) (Martin-Alvarez) and RHex (Figure 9) (Saranli). Both use one motor to drive each of its spoke-like legs in a circle. PROLERO’s chassis rests on the ground, and is lifted up, forward and down by its six spokes. In contrast, the spokes of RHex keep it off the ground by moving through its swing phase quicker than its stance phase. Its legs are compliant so that it can bound when it runs, maintaining a dynamic tripod gait. RHex’ gait is also adaptive to the slope angle of the terrain, and can automatically do specific tasks such as stair climbing or righting itself from an inverted position. In contrast, Whegs™ uses only one motor for propulsion, its multi-spoke legs change their gait passively as a result of their interaction with the environment, and it has a body flexion joint.
1.4 ROBOTS WITH BODY JOINTS.

1.4.1 WHEGS II

Whegs II was the first of the series to have a body joint. The initial inspiration was the observation that cockroaches use their middle legs to rear up and over large obstacles, and then flex their heads down to extend their front legs onto the obstacle and avoid high
centering. Both of these actions can be approximated by the addition of a single body joint that can flex up or down about the middle drive axle (Figure 5). This increased the maximum step height it could climb from 6 to 9 inches for a vehicle with a wheel-leg radius of 4 inches (Allen). It was also observed that the failure mode is not typically that the robot cannot get up the obstacle, but that it instead falls backwards once it is partially on it. This has been termed a ‘high-centering’ failure, and is less likely with a body joint, since it can lower the center of mass of the front section.

Whegs II had gone a long way to validate the concept. The chassis was far more sturdy than its predecessor, Whegs I, and the drive train was able to support a much stronger motor. However, many aspects of the robot were not robust, and usually something had to be fixed after each run. Through discussions with the creator of Whegs II, Tom Allen, and others in the lab, we began to isolate areas for improvement in the design concept. The open chassis design was great for adding sensors and quick repairs, but debris would regularly damage the drive train, and moisture could easily damage the electronic components. Several speed controllers had to be replaced due to shorting. The body joint was wonderfully effective in aiding climbing ability, however, the servo motor used to control it had to be regularly replaced, even though it was the most powerful hobby servo available at the time. The output shaft of the drive servo would regularly snap off. Also, most of the space on Whegs II was taken up by its own drive components. All sensors or control electronics had to be placed on top of the robot.
1.4.2 LUNAR WHEGS

Lunar Whegs is nearly identical in size and shape to Whegs II, but seals the motors and electric components inside two compartments (Figure 10). It was designed by Phil Dunker after DAGSI Whegs was completed. It addresses many of the same design problems found with Whegs II that DAGSI Whegs addresses. Its rugged chassis and drive train can survive sandy and wet environments. Rather than create a large interior space for sensors and additional electronics, Lunar Whegs seals up the minimal amount of electronics and motors that are always on the robot, and modular water-tight compartments can be added on top of the robot as needed. It also has a scoop that is designed to drop down from inside the chassis and collect lunar regolith to be transported back to a possible lunar base where oxygen could be extracted for human use (Dunker, 2009).

Figure 10: Lunar Whegs
The method of sealing Lunar Whegs’ body joint was based on the approach I took in DAGSI whegs, but was actuated in a manner similar to Whegs II. A new servomotor had become available that showed promise of being much more powerful, the HiTec 9885. Two of them work in parallel to lift the body joint via two chain drives and flex-couplings (Figure 11). However, several servos failed and the body joint does not currently work. The exact causes of failure are not known, but several problems became clear. The servos do not generate their rated torque, and they are virtually non-backdrivable. When the robot comes off of an obstacle, it frequently falls on its front wheel legs with the dynamic weight of the robot on the body joint. Since the servos are non-backdrivable, they break before being driven in reverse.

Figure 11: Exploded view of one of two body joint mechanisms on Lunar Whegs.

1.4.3 Asguard

Another robot that post-dates DAGSI Whegs is called Asguard (Figure 12). It is similar to Whegs robots in that it has multiple spokes per wheel-leg. But each wheel-leg is driven by an independent motor, similar to RHex. It has four wheel-legs, which makes it
 statically less stable than six wheel-legs. A completely passive body joint allows the front and rear sections to roll independently of each other. This improves its stability by frequently increasing the number of spokes touching the ground. This kind of body joint may aid in stability during climbing in a way similar to the torsional compliance of Whegs, but it will not significantly increase its maximum climbing ability. Because each wheel-leg is independent, their motions must be coupled in controls. Some sensory feedback such as motor torque and ground contact sensors have been integrated into an abstracted CPG network to create gait adaptation during climbing (Eich).

Figure 12: Asguard, a Whegs inspired robot with a passive roll body joint (Eich).

1.4.4 FRESE

FRESE is another robotic platform that takes inspiration from the Whegs series (REF). Like Asguard, it combines multi-spoked wheel-legs with independent drive motors. This robot has also experimented with some more creative wheel-leg designs, including one called ‘tentacles’ (Figure 13). It is of a similar scale as Whegs II (no dimensions are given) and made of very lightweight and thin polymers. This suggests that the platform is in the early development stages. Nonetheless, some interesting results have come from it. The designers experimented with an entirely passive hinge body joint
slightly forward of the middle axle. In some situations, this proved helpful. Other times, the front body segment would rear up the side of the obstacle, but the rear body joint could not get onto the obstacle (Figure 14) (Siles). An active body joint would give the front wheel legs strong footing on the obstacle at this point in the climb. It seems probable that a passive spring about the joint axis would be more effective than a simple pin joint.

Figure 13: FRESE, a prototype wheel-legged robot with six motors and a fully passive hinge bodyjoint. The front wheel-legs are called ‘tentacle wheels’ (Siles).

Figure 14: Two trials of FRESE, demonstrating varying success with a fully passive hinge bodyjoint (Siles).
1.4.5 Climbing Mini Whegs

The Climbing Mini Whegs series of robots has much in common with its larger counterpart. Early versions had four wheel-legs with scotch tape or structured polymer attached to the ends (Daltorio, 2005). Because these feet can resist tensile forces between the robot and the substrate, they can walk up glass walls, and even transition from ground to wall and from wall to ceiling (interior transitions). However, they could not transition from a wall to the top of an object (an exterior transition) until a body joint was added (Figure 15). In this application, the body joint serves two purposes: as the front feet lose contact with the substrate, they can bend down and make contact again; this also moves the center of gravity over the top of the object (Figure 16) (Daltorio 2008 a, b). Whegs with non-sticky feet benefit from both of these mechanisms during exterior transitions, but in these robots contact can only generate forces normal to the substrate, i.e. they are only effective in compression. This series of wall climbing robots also explored the optimal location of the body joint in simulation, and found it to be near or at the middle axle.

Figure 15: Two versions of Climbing Mini Whegs with different body joints completing an exterior transition.
1.4.6 **AQUA MONKEY**

Aqua Monkey builds on the concept of Climbing Mini Whegs, but uses magnets rather than adhesive to climb ship hulls (Figure 17). The wheel legs are buoyant, and the flexible magnetic strips act as paddles on the surface of the water. An interesting contribution by this robot is that it has a tail instead of rear wheel legs. Since the rear contact point is in compression during vertical climbing, it does not benefit from adhesion and a tail works as well as feet (Keegan). This does make the robot more dependent on the front wheel legs for constant traction, and it cannot make exterior transitions. However, this suggests that a climbing Mini-Whegs with a tail in place of a body joint may be able to make exterior transitions. In fact, a Mini-Whegs with Velcro on its front feet and no rear wheel-legs climbs well on cloth walls.
1.4.7 **AGRI WHEGS**

While working on my design for a new and improved Whegs, I was called in to help finish building another Whegs robot designed by Richard Bachmann called Agri-Whegs. This new platform was much larger than Whegs II, and was initially designed to be water resistant and have a large payload capacity (Figure 18). Working on Agri-Whegs allowed me to test some new ideas, and learn about other design challenges. A new kind of steering mechanism was tested, as well as new foot designs, and a method for sealing the body. Two excellent opportunities arose for testing these new features. We took the robot to Monterey California where we tested autonomous waypoint navigation using GPS and dead reckoning in collaboration with Richard Harkins of the Naval Postgraduate School (Boxerbaum, 2005). We also took Agri-Whegs™ to the Nevada desert where we
ran it on a rubble pile designed for search and rescue training as part of a FEMA/NIST meeting (Figure 19). The feet were highly effective, while the steering design and body sealing methods ultimately did not work. The results of this field-testing resulted in a much more robust platform. In the next section I will go into detail about the problems I encountered, and how I addressed them in DAGSI Whegs.

Figure 18: Agri-Whegs shown with Autonomous waypoint navigation hardware.
DAGSI Whegs™ (Figure 1) is designed in collaboration with the ANT Lab (Advanced Navigation Technology Lab) at the Air Force Institute of Technology. The project is funded by the Dayton Area Graduate Studies Institute, ie. DAGSI. The platform is designed to be a future host to extensive autonomous control hardware, and to deal passively with all but the largest obstacles. This allows computing power to be spent on more interesting tasks like ‘where to go,’ rather than individual foot placement. Previous Whegs™ robots have an open frame, where all components are attached to one of the cross members (Figure 5). This approach allows for a lightweight chassis that is easy to service, but debris can clog the drive train and water can damage the electronic components. Also, the body joints in Whegs™ II and later, Lunar Whegs proved very effective in surmounting larger obstacles, but had to be rebuilt frequently due to impact damage and fatigue. DAGSI Whegs™ addresses these two problems with a novel partially passive body joint and a completely sealed body compartment (Boxerbaum, 2008a, 2008b). These innovations have made it the most robust Whegs™ platform to date, and
we believe it will be very well suited for prolonged autonomous operation over rugged terrain.

2.1 COMPONENT LAYOUT

An early design of the robot had multiple pivot points along the middle drive axle, with the front and rear compartments interlocking like a door hinge (Figure 20). This design is strongly resistant to roll torques, but is mechanically complex, and crowds the already crowded body joint mechanism. Instead, a single joint was designed that can resist torques and forces from all directions. DAGSI Whegs™ is comprised of two body segments that are nearly symmetrical (Figure 21). There is slightly more room in the rear body segment to accommodate the body joint mechanism and motor. The front body segment leaves as much room as possible for sensors and related electronics. The main drive motor is located in front of the first drive axle, leaving a large empty space (17cm X 28cm) for control electronics, enough room for a shock absorbing modular adjustable mounting system that can hold a PC-104 computer (Figure 22). In previous Whegs™ robots, the compliant axle mechanisms (torsional devices) were contained inside the frame. Here, they have been moved outside the sealed frame to save space. All drive chains run just inside the side panels to prevent dividing up the usable space. The front and rear bulkheads of the robot are rounded to allow it to push up and over irregularly shaped obstacles. Windows can be added to the bulkhead to allow video cameras to be stored inside the front body segment.
Figure 20: Initial body joint design with interlocking segments.

Figure 21: Final body joint design with single bearing surface. All drive components and electronics are installed except for the batteries.
2.2 HEAT DISSIPATION

A sealed body prevents heat dissipation, which became a substantial problem for Agri Whegs in the Nevada desert. We destroyed three speed controllers and several batteries. While on site, we installed a fan and several air filters, attempting to maintain the temperature at ambient (106 degrees). A serious cause of heat buildup was the voltage of the motors. In order to keep the battery arrangement as simple as possible, a 12 Volt, 150 Watt Maxon motor was used (run at 14-15 Volts). The startup current was on the order of 150 Amps, which undoubtedly contributed to the failure of multiple speed controllers. One of the speed controllers used in the Nevada desert has a self limiting output that is designed to save it from complete failure. However, the sensor is probably a temperature sensor, so in the extreme heat, the robot acted sluggishly due to the current limiting that kicked in.

DAGSI Whegs also has a 12 volt motor overvoltaged to 16 volts. Although performance has been adequate with the addition of the Victor 885 speed controller, I would suggest that future robots switch to 24 volt motors. Virtually all the commercially
available speed controllers still work in this range, and they will have to deal with much less current at the higher voltage. Because robots of this type are often stalling, it would be advantageous to keep the current draw to a minimum. The battery packs would have to be larger for the drive motors in order to get 24 volts out of the standard 1.5 V cells. However, this would also increase the effective battery life.

In DAGSI Whegs™, the hottest components are kept far away from each other, with the speed controllers in the rear compartment and the drive motor in the front compartment. All speed controllers and the drive motor have a dedicated fan for cooling. The boxes are not completely sealed during normal operation. Along the front and rear of the chassis are two openings that are typically covered with filtration material and a fan forces air through one of them. These can be sealed for an extra level of water protection. No water got in the chassis after operating in large puddles, rain and snow.

A 30 Amp and a 20 Amp automatically resetting fuse run in parallel to make a 50 Amp fuse for the drive motor. When running the 30 Amp fuse alone, it would occasionally trip when climbing stair obstacles. A better route in the future would be to build automatic stall detection into the software. Due to the way the torsion devices wind up, it is very difficult for an operator to visually tell if the robot is stalling or simply winding up the torsion devices.

2.3 Sealing the Body

2.3.1 Agri Whegs Chassis

The Agri Whegs chassis consisted of structural side rails and cross beams. The non structural areas were covered with plexiglass sheets secured with a tongue and groove connection. However, small flexions of the chassis made this interface unreliable, and
despite our best efforts to seal these sheets to the aluminum, dirt always found its way in. This stressed the importance of designing the robot from day-one to have a completely sealed body on DAGSI Whegs.

2.3.2 DAGSI WHEGS CHASSIS

DAGSI Whegs™ can operate completely encased, keeping out dirt as well as water and other contaminants. Both body segments are constructed from a ring of aluminum side panels with carbon fiber top and bottom panels. Each side panel mates with its neighbor with a large surface area, typically 1 cm by 10 cm. This is so liquid silicone gasket can be inserted before assembly to increase water-tightness. However, this makes disassembly more difficult, so it has not been added yet. All screws that connect the side panels were installed from the inside. This prevents any water from seeping through the threading when deeply submerged for long periods of time. However, the inconvenience of installing and removing some of these screws was far too great. As a result, some screws around the middle axle were moved to insert from the outside. This reduces the time it takes to fully disassemble the robot by about eight hours.

The carbon fiber panels are sealed to the side panels using foam backed silicone gaskets. The foam keeps dirt from sticking to the silicone and destroying its sealing properties. As a result, the robot can be easily serviced by removing the carbon fiber panels without breaking the seals between the side panels. Rotary axles penetrate the body of the robot in seven places, one for each wheel-leg and the body joint. U-cup rotary shaft seals are used on the drive shafts, and a single O-ring and grease pack is used for the body joint. During field testing in rain, snow, mud and large puddles, the seals remained intact.
With only minor modifications, this platform could become amphibious. The servos, or alternate steering motors, would need to be waterproofed. The wings that support the front and rear wheel-legs would need to be sealed. The U-joints and torsion devices would also need rust protection.

Each side panel wall is made from a solid piece of 1.27 cm (.5 in) aluminum and consists of a number of standard features. The structural shape is based on a composite C beam, with a large flange on top and bottom (that doubles as the gasketing surface for the carbon fiber panels) connected to each other by a webbing of diagonal support beams. At each junction of support beam and flange is a hub that has one or two mounting holes for additional hardware. In-between the diagonal support beams is a thin outer wall (0.4 mm) that keeps dirt and water out. Because this wall is so thin, it could be at risk of fatigue failure where it meets the diagonal support beams due to the flexion of the entire side panel. In order to alleviate this risk, every one of these transitions is rounded with a quarter-inch ball endmill (Figure 23).
Several of the side walls have a half-cylinder shape. This profile makes the aluminum box much more rigid, as well as providing some other functions. In the front and rear bulkheads, this allows for the robot to push up and over obstacles it encounters. The half-cylinder sections in the middle allow the body joint to rotate without the front and rear sections interfering with each other. These sections were machined by first cutting a large aluminum cylinder with a half-inch wall thickness down the middle, and then mounting them in a specially designed holder so that material could be removed with a CNC machine (Figure 24). Both the drive motor and the body joint motor rely on features machined directly into these curved surfaces. These parts were some of the most difficult to make, but are very light weight, and water proof.
Figure 24: Three stages of machining a bulkhead using progressively smaller ball endmills.

All bearings are press fitted directly into the side walls. This was a particularly nice way to make sure that the spur gear connection between the drive motor and front axle were precisely aligned. Where the axles pass through the outer wall, between each
press-fit bearing and the outer wall of the robot is either an O ring or a U cup seal. These act as shaft seals for the drive axles.

3. BODY JOINT

3.1 MECHANICAL DESIGN OF THE LOAD BEARING JOINT

Connecting the two body segments presents many challenges. More design work and machining time went into the body joint than any other single component. Torque must be transmitted from the front motor to the rear wheel-legs. Power and communication lines must be passed between the two body segments. The body joint must be actuated with a motor and any linkage must be water and dirt tight. This last requirement greatly complicates the design, as compared to previous open-chassis Whegs designs.

Several body joint designs were attempted. Since rotary shaft seals are a known, relatively simple solution, an early design had two sprocket chains mounted outside the sealed body. One chain controlled the body joint, and the other transmitted drive torque (Figure 25). This design takes up a lot of space and has moving parts exposed to the elements. Another design encased the chain sprockets but did not allow for wires to be passed between body segments (Figure 20). Finally, the idea of nested rotary shafts in a coaxial arrangement allowed a compact and water tight design (Figure 26, 27). The outer shaft is rigidly attached to the front body segment, allowing a motor in the rear body segment to actuate the body joint. The inner shaft is the middle wheel-leg drive shaft, which also passes torque to the rear of the robot. The outer shaft can be much larger than the inner shaft, which can leave room to pass wires through between body segments.
Figure 25: Second early design for the body joint.

1. Rear body segment
2. Front body segment
3. Body Joint Motor and transmission
4. Bolt to pre-tension the Belleville springs
5. Bearing mount for drive axle
6. Belleville springs to cushion the worm when backdriven
7. Worm (Not shown: keyway that allows worm to slide axially)
8. Driven worm gear
9. Wheel-leg drive axle, coaxial to driven worm gear
10. Outer raceway of body joint bearing
11. Inner raceway of body joint bearing, interfaces with driven worm gear and front body segment
12. Pass-through between body segments for power and communications lines

Figure 26: Labeled drawing of final body joint design.
Figure 27: Picture of final body joint design.

Unfortunately, conventional bearings at this large diameter are designed for extremely large loads, and have a very large outer diameter. As an alternative, I created a custom bearing surface by carefully machining mating aluminum parts and having them hard-anodized. The outer shaft sleeve was made from a ½” thick plate stock, with a 3.5” diameter circle cut out of it. Both top and bottom edges of the circle were beveled with a specialized routing endmill to have a 1/8” radius. The inner shaft has two parts and clamps together from each side of the outer shaft sleeve. Each inner shaft segment has the inverse profile of the outer shaft sleeve, created by a ¼” ball endmill. All parts were machined to 0.0005” precision, and accounted for the added thickness (0.0002” per surface) that occurs during anodizing. A groove for an O-ring is machined into the outer shaft sleeve holder, and mates to the inner shaft holder just outside the joint. The result is a single joint that can resist both axial and radial loads and is watertight.
3.2 Actuation of the Body Joint

Whegs™ II, the first Whegs™ robot with a body joint, used a large backdrivable servo, which allowed the motor to absorb some of the shock of impact, but constant current draw quickly drained the batteries and affordable commercial servos were not rugged enough for repeated impacts. To remedy this, Whegs™ III used a non-backdrivable worm gear. However, the teeth of the gear sheared off under impact loading. While it would be possible to design a worm gear drive with teeth large enough to survive most impacts, this device would be very heavy and would have no passive adaptation to the terrain. It was clear that a new body joint actuation system needed to be developed.

The solution in DAGSI Whegs™ is a compliant, non-backdrivable body joint (Figure 26, 27). Compliance and non-backdrivability are achieved with a novel design. In forward drive, the system works like a traditional non-backdrivable worm gear (Fig 28a). A worm is driven by a motor via a key in the keyway, but unlike traditional worm gears, it is free to slide axially along the shaft, where it is held in place on both sides by Belleville springs. The worm drives a driven worm gear, which is fixed to the outer shaft of the coaxial arrangement, which is in turn fixed to the front body segment. In reverse drive, the system acts similar to a rack and pinion, where the driven worm gear is the pinion, and the worm is the rack (Fig 28b and 28c). When the front wheel-legs impact an obstacle, the front body segment rotates up, rotating the driven worm gear, which pushes the driving worm axially into the Bellville springs. Regardless of the passive state of the body joint (the amount of compression in the Belleville springs), the motor can actuate the body joint in either direction. Any compression spring can function to keep the worm in place.
However, due to the proximity of the worm to the center of rotation, a very stiff spring will be much less stiff under this mechanical advantage. Bellville springs offer the stiffest solution at this scale.

Figure 28: Diagram of the body joint under three different loading conditions, a, b and c.

This body flexion joint design also allows the passive stiffness of the body joint to be independently tuned in the clockwise and counter-clockwise directions by changing the number and stiffness of the Bellville springs on either side of the worm. When run autonomously, it may be advantageous to have a lower stiffness body joint that works entirely passively to overcome obstacles. When in radio control mode, the body joint stiffness can be higher to allow more responsive user control.

Changing the stiffness of the body joint currently requires that one disassemble the body joint mechanism, a procedure that can take a few hours when it goes smoothly. Because of this, there has not been a systematic testing of different stiffness. One can change the shape of the stiffness curve slightly by adjusting the pre-tensioning bolt. Typically, the body joint angle/torque relationship has two linear sections. The first occurs
when both Bellville springs are pushing on the worm in opposite directions. However, once one set of springs is compressed enough, the other will no longer touch the worm. At this point, the slope of the line decreases (Figure 29). The point at which this transition occurs can be tweaked by increasing or decreasing the spring pre-tension. However, this does not change the slope of the two line segments because the forces cancel each other.

![Diagram of force verses displacement](image)

**Figure 29:** Conceptual force verses displacement of the body joint worm gear with no damping. The blue and red lines are the independent spring functions for the left and right side Bellville springs, while the green line is the effective combined force-displacement relationship. At the point ‘b’, one spring is fully extended and stops touching the worm gear, so its force goes to zero. At the point ‘a’, the compressed spring bottoms out, and the body joint becomes rigid in that direction. The pre-loading distance ‘d’ can be adjusted manually to change the point at which the slope changes, and the maximum range of motion of the passive compliance.

This design essentially puts a spring in series with an actuator and is similar to a series elastic actuator used in several robotic applications (Robinson). Currently, we are not using the displacement of the springs to measure force, but rather using the system as a
form of a suspension. This non-backdrivable design is also inherently rotary, eliminating the need for cables.

3.3 FIRST PROTOTYPE BODY JOINT

Prior to designing the robot, a prototype of this new kind of actuator was built in order to test its feasibility (Figure 30). With a 20 W motor and a 23:1 gear reduction, our calculations predicted a stall torque of 83.5 Nm and a slew rate of 56 deg/sec under a torque of 14.7 Nm. Experimentally, we were not able to find the stall torque because one of the two axial ball bearings that supported the Bellville springs failed while testing a load of 26.4 Nm. Resonant vibrations were observed, which may have contributed to the failure.

Figure 30: First working prototype of the body joint mechanism.

With the exception of the bearing failure, the body joint performed as expected. The
passive compliant range of motion of the Bellville springs was ±12 degrees, slightly less when tested with stiffer springs. The body joint could rotate over a full 360 degrees without variations in speed, and rotate continuously. Shaking the lever arm in all directions did not appear to affect the performance. Changing the Bellville springs was relatively easy and changed the stiffness of the lever arm as expected (Boxerbaum, 2005).

### 3.4 Body Joint in DAGSI Whegs

The bearings in this early prototype were angled ball bearings designed to take both axial and radial thrust. However, the axial thrust rating was relatively low compared to a thrust bearing, and was only rated to the static torque of a motor under stall. In DAGSI Whegs, I replaced these ball bearings with custom made Delrin bearings that have a much lower profile and resist both axial and radial loads equally well.

The body joint worm axle has to extend well beyond the worm in both directions in order to make room for the Bellville springs. In order to achieve this, one axle bearing hole was machined directly into the side wall, and the custom bearing was inserted into it. This was particularly tricky since it involved several parts aligning correctly so that the worm meshed nicely with the driven worm gear (Figure 26, 27).

The two coaxial shafts used in this body joint do not have to be of the same diameter. By making the larger shaft 8.9 cm (3.5 in) in diameter, cables can be passed from the front to rear sections.
3.5 The Effect of Body Joint Torques on the Robot

I discovered by chance that the location of the drive motor has important implications for the robot. Agri Whegs has its drive motor in the rear section and was meant to have a body joint, but it was not completed at the time of testing in the Nevada desert. As an experiment, I unlocked the un-acutated body joint and ran it over a very small obstacle. To my surprise, the body joint quickly buckled, causing the front body segment to pitch downward (the opposite of the desired direction in this early stage of the climb). This made me realize that the body joint and drive motor torques must be coupled in some way. The motor generates torques that are passed to the wheel-legs. However, it can only do this by applying an equal and opposite torque to the chassis of the robot. When the motor is in the front body segment, this torque causes the front to rear up about the body joint hinge. When the motor is in the rear body segment, the torque is the same, but it causes the rear body segment to rotate down (Figure 31). When combining this with the passive compliance of the body joint, it becomes clear that it is important to have the drive motor in the front. In this configuration, when the robot encounters obstacles and the motor experiences high torques, the passive response is to rear up slightly.
Figure 31: Free body diagram of the effect of motor torque (red) on a robot with a body joint as compared to the torque of the body joint motor (orange) (disregarding robot mass). If the robot is free to rotate about the green dot, then the moment supplied by the body joint motor must be equal and opposite the drive motor moment. Otherwise, the front section will rotate clockwise about the body joint.

This problem of the drive motor torquing the chassis causes fundamental tradeoffs. In order to lift the weight of the front chassis, the body joint drive motor can be a small, lightweight 20 Watt motor. However, this means that the drive motor is entirely capable of overpowering the body joint motor at the body joint. Due to the conservation of angular momentum, the entire drive torque is passed through the body joint. The two motors fight each other with the same mechanical advantage. Adding a very large body joint motor would add weight, and decrease efficiency. In the initial configuration with a 20 watt body joint motor, the body joint can only lift the weight it needs to when the drive motor is trying to drive forward. However, when the robot gets partially up on an obstacle and the body joint needs to quickly flex downward to prevent high centering, it cannot do this if
the drive motor is actuated. After some practice, a trained operator can learn to use this to one’s advantage. If the robot is statically stable half way up the obstacle, the drive motor can be gently torqued in reverse in order to help the body joint motor. This strategy may be difficult to implement autonomously due to the risk of the robot moving backwards.

The fact that the body joint experiences the entire drive motor torque should be a final argument for the need to have a non-backdrivable body joint. In any backdrivable arrangement, the two motors will needlessly torque against each other at the cost of huge current draw. However, even under a non backdrivable arrangement, the body joint motor will not be of use when it has to compete against the drive motor. The passive compliance of the body joint provides some assistance with this problem of body joint actuation. The drive torque fluctuates as the robot moves forward. If the body joint motor attempts to move the body joint when the drive motor is torquing against it, the body joint doesn’t move, but the Bellville springs become loaded. When the drive torque becomes smaller, the springs then convert that stored energy into an angular displacement of the body joint. In this way, the body joint can ratchet itself up when the situation is amicable.

When driving on relatively flat ground, the passive compliance in the body joint can cause an interesting problem. A rigid body is stable on the ground if it has three contact points; however, now the robot is essentially two rigid bodies connected with a rotary spring. The result is that the body joint naturally flexes downwards and the robot rolls to the side until the swing middle wheel-leg touches the ground. When running forward, the robot rolls back and forth with each tripod transition. The problem can be avoided by simply flexing the body joint upwards until the stiffness is great enough to counteract the dipping of the body joint. However, this distributes the loads back to the
front and rear wheel legs, which may have other consequences in terms of maintaining even ground contact.

3.6 MOTOR UPGRADE

The first body joint motor was a 20 W Maxon motor with a stall torque of 0.22 Newton meters (Maxon Motor # 118752) and a 23:1 transmission ratio (Maxon Trans# 166936). This was largely out of convenience, since the motor was available from another project. The worm and driven gear have a ratio of 40:1, giving a final gear ratio of 930:1. But only a 33% efficiency. The motor torque calculations showed that this motor should be sufficient to lift the body joint front half. (Appendix B). However, this was not the case. The front of the robot had become more heavy due to the relocation of the main drive motor. Another possible problem may be the inefficiency of the worm drive system. I used an efficiency rating of 45% for the worm gear, but it may be lower. Finally, the large greased outer bearing surface may have contributed significant resistance to the motor. Since it has a diameter of 4", the resultant moment caused by the friction in the joint is very large. If a typical joint with this payload capacity has a quarter inch diameter, and here we have a four inch diameter, this results in 16 times the frictional torque.

While this motor was still able to lift the body joint with the help of the drive motor, it would be preferable to have a more independent body joint. A 60 W motor was selected with a stall torque of 0.99 Newton meters (Maxon Motor # 310006) and a 14:1 transmission ratio (Maxon Trans# 166933). This motor is just strong enough to lift the front body segment without the help of the drive motor. Nonetheless, it is not strong enough to defeat the drive motor when it is fighting the body joint motor.
4. **Steering**

The vast majority of Whegs robots are steered with servos that rotate its front and rear wheel-legs in opposite directions. For instance, to turn left while moving forward, the front wheel legs rotate counter clockwise when viewed from above, and the rear wheel legs rotate clockwise. When it works well, all wheel legs move forward along a single curved trajectory. The nice thing about this kind of steering is that it requires only one drive motor (as opposed to differential steering), and it is mechanically simple, and intuitive for teleoperation (Figure 32). A single drive train also locks in the preferred phasing of the wheel legs, thus eliminating a substantial control problem.

![Walking:](image)

Figure 32: Diagram showing how DAGSI Whegs steers.
4.1 Early Steering Mechanism Designs

Robots that interact with rugged terrain are subject to frequent impact forces. The torsional axle devices in Whegs robots that provide compliance to the terrain also damp out a great deal of these forces from the drive train. However, the steering drive linkage is still exposed to these impacts.

In Agri-Whegs™ we tried using cables to link its steering motors to its wheel-legs (Figure 33). This allows for a more compact design and consistent torque over wide range of motion. Several different kinds of cable were tried, including Spectra, Kevlar and aircraft steel. The reoccurring problem was breaking or loosening of the cable due to fraying at the attachment points. A thick steel cable with nylon coating appears to offer a practical solution. However, because of these complications, DAGSI Whegs™ used a direct-drive power linkage, with a motor servo directly above each turning wheel-leg (Figure 34). My hope was that the servos would be backdrivable enough to absorb the impacts of steering in a rugged environment. However, we discovered that this was not the case, as several servos were destroyed in moderate testing.

Figure 33: Cable steering mechanism on Agri Whegs.
4.2 The Effects of Ground Reaction Forces

A robot with wheel-legs has some interesting properties as compared to its wheeled equivalent. It doesn’t need a differential between left and right wheel-legs, because each wheel-leg has frequent swing and stance phases. The fact that the inner wheel-leg does not travel as far as the outer one during a turn is compensated by the naturally occurring shorter swing phase on the inner wheel-leg. At first, I was under the impression that this also meant Ackerman steering (where all wheels paths have the same center of curvature) was also not essential. For this reason, I made each wheel leg independently steerable. This meant that with the flip of a switch, the robot could go from normal steering to something akin to crab walking. However, this setup had some negative consequences. I noticed that with four independently steered wheel-legs, the inner wheel legs had a far greater effect on turning ability than the outer ones. In fact, sometimes
turning the outer wheel legs would impede turning. It was also the most common cause of breaking a servo. Small bumps in the ground would cause the outer wheel leg to oversteer. The forward momentum of the robot would then force the wheel leg tighter into its turn, and break a steering servo in the process (Figure 35).

![Figure 35: Diagram of common steering failure.](image)

When the robot is turning at a constant velocity, ideally all ground reaction forces only contribute to the acceleration required to turn. This is best achieved with an Ackerman steering arrangement because the ground reaction forces from a wheel or wheel leg will be perpendicular to the motion of the wheel. By keeping every wheel-leg’s path concentric, the wheel-legs cannot fight each other. A free body diagram (Figure 36) demonstrates why the inner wheel legs have a greater effect on turning. They are positioned such that about the center of mass, the moment arm of forces normal to the wheel leg is greatest, so the resulting moment is almost twice as large as the outer wheel legs.
4.3 REVISED STEERING DESIGN

As a result of these initial failures, I made several design changes. I connected left and right wheel legs via a tie rod and arranged the geometry of the tie rod linkage to create Ackerman steering (Figure 33). I placed a damping element in between each servo and the steering upright, and limited the range of motion of each wheel-leg with an adjustable mechanical stop (Fig 38).
Figure 37: Tie rod connecting left and right steering servos to give Ackerman steering. When assembled, this tie rod sits inside the cross bar below it.

Figure 38: Damping element in between servo and steering linkage. The servo (not shown) screws into the top of the crossbar.

The steering linkage also transmits random forces encountered due to variance in the terrain from one wheel leg to the other, which shares the load, thus sparing the servo from large loads.
Part of the problems with the steering can be attributed to the hobby servos that were used. Hitec rates these hobby servos at 416 inch-ounces of torque. It is very unlikely that it can actually produce this much torque, and the servo is generally under-designed to take such loads (Dunker, 2009). Two servos failed due to spur gear teeth shearing, and two more failed due to overheating. Since each servo can generate a great deal of torque, it becomes quite determined to get exactly where it wants to be, and generates a good deal of heat in the process. These servos would draw two to three amps at 7 volts even if the position error was small. On a different robot, this model servo failed due to overheating when a much weaker model servo worked fine due to its backdrivability and lower current draw. Future Whegs robots at this scale should probably use custom motors instead of hobby servos, and add more compliance in the steering drive train.

5. **Power Drive Train**

The power drive train was designed to transmit the full motor torque to any wheel-leg. The motor was sized based on our desire to move at two body lengths per second, and climb up stairs or a 35 degree slope with a total weight of 35 lbs (Appendix A). Originally, the motor was designed to be in the rear of the robot. However, after field testing of Agri-Whegs, it became clear that having the motor in the front body segment would benefit the body joint actuation. The design was reworked to accommodate having the motor near the body joint in the front segment. However, once it became clear that the very front of the chassis was not going to be used for sensors, as originally thought, the motor was moved to the very front of the robot. With it so close to the front drive shaft, a spur gear made more sense than a sprocket and chain (Figure 39).
After some field testing of this design, it became clear that the wheel legs have different maximum torques, depending on their proximity to the drive motor. In the current arrangement, the front wheel legs are the strongest due to the minimal losses in friction. The rear wheel legs are the weakest, and have the most amount of play in the drive train. Shaft strength greatly depends on the precision of the machining, so I placed the most well machined shaft-hub interfaces at the front of the robot.

In previous Whegs robots, a wide range of power train shaft-hub interfaces have been tried, including a radial pin, set screw and flat on shaft, hex shaft and broached hex hole. All of these methods have had their benefits and problems. Between the six torsion devices and four U-joints, there are thirty-one shaft-hub interfaces on DAGSI Whegs. Therefore, it is very important to choose a method of transmitting torque that is efficient to
machine, accurate, and strong enough. Primarily because of all the problems with the previous methods, I chose the only commonly used method not yet tried on a Whegs platform: keyed shafts. I also made eighteen custom steel hubs to interface with the shafts. Two spur gears, three sprockets and four U-joints also required major modifications. The end result has held up exceptionally well, with little play, and no failures to date. However, this solution was very time-consuming to machine. The steel hubs are also quite heavy, despite my best efforts to keep the weight down. Also, each shaft needed to be machined to allow multiple keys. Careful consideration was always needed to make sure that the wheel legs could be aligned in the end to have proper phasing.

Two sprocket chains transmit the torque between front, middle and rear drive axles. These chains are positioned as close to the side walls as possible, to prevent the primary payload space from being divided up (Figure 37). Typically, sprocket chains have a chain tensioner to decrease the likelihood of a derailment. This application is rather unique, in that the sprocket chains must provide torque in both forward and reverse walking. During forward walking, the top chain is in tension, and the bottom chain is loose. During reverse walking, the opposite is true. This fact precludes the vast majority of chain tensioner designs, which use a spring to apply tension to the loose chain. Agri-Whegs solved this problem by making each axle bearing adjustable, such that the chain was always snug. However, there is no good way to make such a design waterproof, since the axles protrude through the body. My solution was to build a chain tensioner that applies a force between both top and bottom chains, instead of between a single chain and a fixed element (Figure 40). Such a device would tend to slide towards one gear or the
other and jam there, so it is constrained to slide in the vertical direction, perpendicular to the motion of the chain.

![Bi-directional chain tensioner](image)

Figure 40: A bi-directional chain tensioner made of white Delrin that is constrained to move vertically by a groove in the removed side panel.

6. TORSION DEVICES

6.1 THE BENEFITS OF TORSION DEVICES

The torsional devices in previous Whegs robots have varied greatly in design (Figure 41). The functional goal is to have the drive torque transmitted from the motor to the wheel-leg, until a threshold torque is reached. At this threshold torque, the input drive shaft continues to rotate, while the wheel-leg remains stationary. After a set amount of rotation, a mechanical stop delivers the entire motor torque to the wheel-leg. Usually the
amount of rotation is set so that corresponding right and left wheel-legs are in phase when they both start moving together. This has several advantages. When climbing, roll stability can be a major problem in legged robots. If contact is better on one side, the robot will roll over toward the other side. The torsion devices increase the probability that the ground contact is more evenly distributed by allowing the wheel legs that are under the greatest load to stop rotating, while the unloaded wheel-legs rotate forward until they have ground contact. Also, if one wheel-leg gets stuck, the other five have opportunities to push before the drive train becomes stuck.

Figure 41: Two previous torsional devices.
6.2 Torsion Devices in DAGSI Whegs

The torsion device mechanism for DAGSI Whegs consists of a cup that holds a torsion spring. The output axle passes through the spring and terminates at the bottom of the cup in a butterfly like steel shape that also holds one end of the torsion spring. The shape of this butterfly defines the range of motion, as it contacts the interior of the cup at both the limits of the range of motion (Figure 42). The pre-tensioning can be adjusted in 60 degree increments by placing the lid on under the desired load. The lid holds the input end of the spring and attaches to the cup directly.

![Figure 42: Torsional devices outside the main body on DAGSI Whegs.](image)

Using torsional springs present many challenges. The springs deform greatly when wound up over 360 degrees, contracting radially by as much as 30% and expanding by the thickness of the wire for each full turn. If the spring is not carefully constrained, it will become crooked inside the device and come loose, but if it is over constrained, the spring will buckle under its own pressure and deform irregularly. After several iterations, the final design provides just the right amount of freedom to allow the spring to operate by adding a groove to the lid of the device to keep the spring in proper alignment (Figure 42).
Because the middle torsion devices are inboard, it is a challenge to change the pre-loading once installed. In future designs, the middle wheel-legs could have the torsional devices embedded into the hub of the wheel. This would free up even more space inside the robot and make them easy to access.

7. Foot and Wheel-Leg Design

7.1 Foot Designs

Two kinds of feet were tested on Agri-Whegs. One was designed for grassy fields and soil and consists of an aluminum spike or claw offset from the spoke. It worked quite well on those substrates. Using these feet, the robot was able to climb up a 32 degree slope hill. However, these feet are not suited for hard or sandy surfaces. On sand, there is not enough surface area to keep it from sinking. Indoors, the sharp points cause harsh impacts and damage floors. An alternate design was developed for more general use. It consists of an aluminum and rubber foot with wave treads (Figure 43). This was tested in the Nevada desert and appeared to work very well on rocks, gravel, packed dirt, and even hotel room floors. An innovation in this design was that these wheel-legs had a zero-scrub radius: the center of the foot lies directly below the steering axis of rotation. This eliminates any moment about the steering axis caused by ground reaction forces. The result is much better controllability, particularly at high speeds, and less wear on the steering servos.
Figure 43: Indoor feet on Agri Whegs (left) and DAGSI Whegs (right).

DAGSI Whegs feet also have a zero scrub radius (Figure 44). Instead of having two kinds of feet, a single aluminum foot with a rough surface can be covered with a rubberized booty made from bicycle tread for indoor use.

Figure 44: Outdoor feet on DAGSI Whegs with a zero-scrub radius.
7.2 Wheel Leg Design

The spokes of Agri Whegs are made of quarter inch aluminum plate stock and screwed on individually to the hub. This made it easy to replace a damaged spoke, but added weight due to the need to design around the stress concentrations at the hub and extra screws. Another problem was observed when Agri Whegs attempted to climb stairs. When approaching the first stair, the leading edge of the obstacle would make contact with the front chassis of the robot before the foot landed on the top of the stair. The result was that the robot would attempt to push the stair horizontally, rather than climb up and over it. Often, backing up and changing the phase alignment of the wheel-legs was enough to fix the problem. (Figure 45)

Figure 45: Agri-Whegs getting stuck on a stair due to contact between front of the robot and the stair.

DAGSI Whegs eliminated these problems by using a single wheel-leg with three spokes machined out of a single sheet of aluminum. A large aluminum hub with a 5” diameter surrounds the inner steel hub to prevent obstacles from getting too close to the
chassis (Figure 44). This integrated design is stronger and lighter than its predecessor. While damage to a spoke would mean that the whole wheel leg would have to be re-machined, such damage hasn’t occurred during field testing.

Figure 46: DAGSI Whegs’ large aluminum hub and rounded bulkhead prevents it from getting stuck on stairs.

8. DYNAMIC SIMULATION

A two-dimensional dynamic simulation of the robot was created using Working Model 2D 7.0. This allowed us to study several variables that affect climbing ability without risk of damage to the robotic platform. During climbing a regularly shaped step obstacle in the real robot, the left and right wheel-legs slide into phase with each other, due to the torsional compliance. This load sharing greatly improves roll stability. This allowed us to simplify the 2D model as a robot with only three wheel-legs (Figure 47). We also assumed that all three wheel-legs moved together with a constant velocity regardless
of the torque. The weight distribution of the simulation was based on the robot, but a 4 kg mass representing batteries and payload was moved to different locations fore and aft to observe the effect on climbing performance.

Figure 47: Working Model simulation of DAGSI Whegs with an actively controlled, passively compliant body joint and an adjustable center of mass.

The body joint model has a torsion spring and damper about the middle drive axle. The rest position can be changed in real-time during the simulation either by an observer, or based on an autonomous control algorithm. Here, the body joint was controlled by the user in real-time in order to recreate the current testing environment.

At the onset of making this model, I was under the impression that I could interface Matlab with Working Model in order to test autonomous control strategies, and
to possibly automate an optimization of many design parameters. However, after many attempts, it was found out that a bug in the Working Model software would not allow this. There are some reports that this bug has been fixed recently.

It should also be noted that Working Model 2D has several idiosyncrasies that make it important to use caution when interpreting the data from simulation. The interactions between the ground and the robot are very difficult to model well, and I have reason to believe that this software does not do a good job in certain situations. If the robot velocity was too great upon impact, or if either ground or robot were irregularly shaped, the simulation would appear to fail in that the robot would fly up into the air, clearly violating all energy conservation laws. Attempts to change the time step size did not help. These situations were avoided during the systematic testing, and when they clearly arose, that data was disregarded. It is not easy to tell with this software if there are more subtle effects on the data. One of the best indicators that the simulation may be useful is that the predicted and actual maximum obstacle heights under many different conditions are very close.

9. PERFORMANCE EVALUATION (RESULTS AND DISCUSSION)

Extensive field testing was performed under many different conditions. DAGSI Whegs™ was able to climb a 34 degree muddy slope and climb stairs of a variety of dimensions, including full height stairs indoors and outdoors (Figure 48). It could navigate rocky snow covered fields, and construction sites (Figure 49). The robot performed equally well indoors with the addition of padded feet. The body remained sealed during all tests. The steering servos occasionally failed, as discussed in Section 4. The modifications made to the steering linkage have thus far prevented any further failure. The passive
compliance of the body joint has made it exceptionally robust. Future testing of different stiffness Bellville springs will help elucidate its role in climbing and walking. Detailed records of runtime were not kept. I estimate that the robot has been run well over 50 hours without mechanical failures.

Figure 48: DAGSI Whegs climbing up stairs and a steep incline

Figure 49: DAGSI Whegs in the snow.

9.1 POWER CONSUMPTION

Whegs™ has a single 150 watt drive motor powered by two 8 V 4100 mAh Nickel
metal hydride batteries connected in series. On relatively level terrain with an occasional obstacle, it ran for over three hours continuously. During obstacle climbing trials where the robot stalls more frequently, the battery life was an average of 45 minutes, at which point it could not lift its weight up the obstacle. In the near future, the addition of automatic stall detection should increase battery life.

9.2 QUANTITATIVE TESTING OF OBSTACLE CLIMBING

To further quantify climbing ability, an adjustable height obstacle was constructed in the shape of a single step. In the first round of experiments, the maximum height of the obstacle was found for the robot with a locked body joint, and with an actively controlled body joint (Figure 50). The batteries were placed to achieve a center of mass coincident with its center of geometry. With a locked body joint and a wheel-leg radius of 17 cm, the maximum height step the robot can overcome is 27 cm. On larger obstacles, the vehicle high-centers and falls backwards (Figure 51). The middle wheel-legs can get on to the obstacle, but the resultant force appeared to push the robot’s center of mass behind its ground-reaction forces.

With an active body joint, an obstacle height of 33 cm was overcome, a 22% increase over the locked body joint. Initially, the robot flexes its front end up to help the foot land flat on top of the obstacle. Once the front wheel legs are situated on top of the obstacle, the front body segment flexes down, lifting the middle wheel-legs up, allowing them to get a foot-hold on top of the obstacle. The robot then moves forward and once the center of gravity of the robot is on top of the obstacle, it slowly flexes its front segment up again to allow the rear legs to climb up (Fig 52).
Figure 50: DAGSI Whegs climbing a 27 cm obstacle with a locked body joint.

Figure 51: DAGSI Whegs with a locked body joint falling backwards off a larger obstacle.

Figure 52: Stills from a video sequence of DAGSI Whegs climbing a 40 cm obstacle.
During testing of the actual robot climbing, it became clear that high-centering was the primary mode of failure. From close examination of the videos, it appeared that the position of the center of mass relative to the middle foot placement when it reaches the top of the obstacle was critically important. If the center of mass appeared to be behind the foot, the robot would fall back and high-center off the obstacle; if the center of mass was in front of the foot, the robot would fall forward on top of the obstacle and successfully complete the task. This rule of thumb is probably the result of a balancing act between three competing moments. On the one hand, the drive motor torque wants to rotate the entire robot backwards away from the obstacle. On the other hand, the wheel leg drive axle applies a force on the robot that may be along a line above its center of mass relative to the ground contact point. This is especially the case if the robot is bending down to reach over the obstacle. Lastly, gravity pulls the robot down, and will cause it to rotate about a single ground contact point. These three moments determine if the robot rotates forward onto the obstacle or falls back away from it. (Fig 53).
Figure 53: Free body diagram of a Whegs robot at a critical point in an obstacle climb.

9.4 RESULTS FROM THE SIMULATION

We were able to test this theory in our simulation without risk to the robot. The simulation confirms that the weight distribution has a significant impact on climbing ability, particularly with an active body joint [Table 1]. By moving a 4.7 kg mass from the center of the robot to the front of the robot, the maximum height obstacle it could repeatedly overcome went from 32 cm to 38 cm, a 6 cm increase. By redistributing 6 kg to
the front of the robot, a 40 cm obstacle was consistently overcome. Obstacles as high as 46 cm were overcome, but not repeatedly.

<table>
<thead>
<tr>
<th>Experimental / Simulated</th>
<th>Total body weight (kg)</th>
<th>Center of Mass (cm)</th>
<th>Body Joint</th>
<th>Max Height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated</td>
<td>21</td>
<td>0</td>
<td>Locked</td>
<td>30</td>
</tr>
<tr>
<td>Simulated</td>
<td>21</td>
<td>7.4</td>
<td>Locked</td>
<td>30</td>
</tr>
<tr>
<td>Simulated</td>
<td>21</td>
<td>0</td>
<td>Active</td>
<td>32</td>
</tr>
<tr>
<td>Simulated</td>
<td>21</td>
<td>7.4</td>
<td>Active</td>
<td>38</td>
</tr>
<tr>
<td>Simulated</td>
<td>21</td>
<td>11.2</td>
<td>Active</td>
<td>40</td>
</tr>
<tr>
<td>Experimental</td>
<td>20</td>
<td>0</td>
<td>Locked</td>
<td>27</td>
</tr>
<tr>
<td>Experimental</td>
<td>20</td>
<td>0</td>
<td>Active</td>
<td>33</td>
</tr>
<tr>
<td>Experimental</td>
<td>21</td>
<td>7.4</td>
<td>Active</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 1: Summary of climbing ability of a Whegs robot with a body joint in simulation and experiment. In simulation, successful climbing was considered three successful climbs in a row. In experiment, successful climbing was limited to two climbs in a row, in order to limit the risk of damaging the platform. The Center of mass dimension is the distance from the center of geometry to the center of mass, positive values meaning it is forward of the center of gravity.

Stairs present a different challenge from single obstacle climbing. The repetitious nature of the obstacle means that if a foot lands a few inches from the crux of the stair, then it will land even further back on the next stair, until the foot misses a stair, and the robot falls back slightly. Wheel-legged platforms have been designed that successfully climb stairs smoothly, but any particular design must be specific to that stair dimension. While working with the simulation, a novel use of the body joint was found that may help this platform climb any set of stairs. By flexing the body joint down slightly, the robotic platform can adjust where the foot lands, and prevent it from working its way off the stairs. This technique works for may different dimensions of stairs in simulation (Figure 54), but has not been validated in practice.
Dynamic simulations of highly unstructured environments were also undertaken (Figure 55). With an actively controlled body joint, the model made it through the environment in Figure 55. The body joint was key in allowing it to free stuck wheel legs. Such environments will be useful for testing autonomous control strategies.

9.5 More Quantitative Testing of the Robot

Once it became clear that the location of the center of mass was likely a significant factor in climbing ability, a second round of experiments was undertaken. The batteries, which weigh 2 kg, were moved from the rear to the front of the robot, and an additional 1
kg of weight was added. This moved the center of mass 7.4 cm forward of the center of geometry (found experimentally). The result was that the robot successfully climbed a 40 cm obstacle (2.19 times the length of a leg) (Fig 56) (Table 1).

Figure 56: DAGSI Whegs climbing a 40 cm obstacle.

9.6 ALTERNATIVE DESIGNS IN SIMULATION

Based on our observation that having the center of mass forward of the center of geometry, and that the rear wheel legs do not contribute significantly during the last phase of exterior transitions, I wondered if a robot with four wheel legs and an actuated tail rather than a body joint would perform as well. This would make for a lighter robot (albeit with less payload capacity), less mechanical complexity, and open the possibility for using skid steering, which could give a zero turn radius. The working model simulation that I made has a tail that extends to the length of the six wheel-legged model. Surprisingly, in simulation, this design out-performs the six wheel-legged model in maximum climbing
height (Figure 57). In fact, it almost never high centered. Instead, the limiting factor was whether or not the robot could get an initial grip on the top lip of the obstacle. The maximum height obstacle it overcame was 46 cm, 6 cm higher than its body jointed counterpart (Table 2).

Figure 57: Simulation of a four wheel-legged Whegs robot with a tail.
As a result of the success of this simulation, the next generation of Whegs robots, Pelican Whegs, will have a tail rather than a rear body segment (Figure 55). This tail can be used to climb high obstacles, or to swim in surf zones. By angling the tail in the oncoming current, the robot may gain more ground traction, similar to the way lobsters use their tails. (Ayers).

Table 2: Comparison of climbing ability in simulation of a Whegs robot with six wheel-legs and body joint to one with four wheel-legs and a tail. The robot with the body joint climbs well with the body joint active and the center of mass moved forward. The robot with only a tail can climb the highest, but does not significantly benefit from moving the center of mass any further forward.
Figure 58: Pelican Whegs
10. CONCLUSIONS

The goal of the DAGSI Whegs project was to make a rugged version of the Whegs concept vehicle with a large payload capacity for autonomous operations. Although DAGSI Whegs has not been run autonomously, field testing has shown it is ready for such operations. Unlike previous Whegs robots, getting DAGSI Whegs ready for a demonstration only consists of making sure the batteries are charged. The new actively controlled, passively compliant body joint is both rugged and useful, increasing the maximum obstacle height by 22%, and allowing it to extricate itself from potential jamming situations. To date, it is the only Whegs body joint to have never failed. The structural box design is light weight and spacious. On several occasions after being built, the component layout was changed. These changes required less than a day to implement due to the flexible architecture. As a trade off, the design and machining of the structural box took considerable time in order to ensure strength and flexibility. New designs of the wheel-legs, torsion devices and steering mechanisms proved effective.

The two-dimensional dynamic simulation of the robot was very useful in studying the effects of weight distribution on obstacle climbing. Moving the center of mass forward in the actual robot increased climbing performance by another 18%, which fit the predictions closely. The simulation also suggests a new four wheel-leg design with a long tail that is currently being designed.
### APPENDIX A: DETAILED COMPARISON OF SEVERAL WHEGS ROBOTS.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Whegs I</th>
<th>Whegs II</th>
<th>DAGSI Whegs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length</strong></td>
<td>19.5 inches</td>
<td>18.5 inches</td>
<td>36 inches</td>
</tr>
<tr>
<td><strong>Width</strong></td>
<td>19.5 inches</td>
<td>14 inches</td>
<td>21 inches</td>
</tr>
<tr>
<td><strong>Chassis Height</strong></td>
<td>2.5 inches</td>
<td>2.25 inches</td>
<td>4 inches</td>
</tr>
<tr>
<td><strong>Spoke Length</strong></td>
<td>4.5 inches</td>
<td>4 inches</td>
<td>7.5 inches</td>
</tr>
<tr>
<td><strong>Max Ground Clearance</strong></td>
<td>2.75 inches</td>
<td>2.875 inches</td>
<td>5.5 inches</td>
</tr>
<tr>
<td><strong>Chassis Material</strong></td>
<td>Delrin</td>
<td>6061 aluminum</td>
<td>6061 Aluminum and carbon fiber</td>
</tr>
<tr>
<td><strong>Steering Configuration</strong></td>
<td>Pushrod type, ±20 degrees travel, 2 Hitec HS-300 servos</td>
<td>Pushrod Type, ±30 degrees travel, 2 Futaba S3000 servos</td>
<td>direct drive servo with Ackerman constraint.</td>
</tr>
<tr>
<td><strong>Turning Radius</strong></td>
<td>30 inches (1.5 body lengths)</td>
<td>23 inches (1.25 body lengths)</td>
<td>21 inches (0.6 body lengths)</td>
</tr>
<tr>
<td><strong>Hubs</strong></td>
<td>Delrin</td>
<td>Aluminum</td>
<td>Steel</td>
</tr>
<tr>
<td><strong>Legs</strong></td>
<td>Steel tubing</td>
<td>Prismatic spring loaded joint, steel</td>
<td>Single piece aluminum</td>
</tr>
<tr>
<td><strong>Feet</strong></td>
<td>Spring steel with rubber sleeve</td>
<td>Aluminum partial rim</td>
<td>Aluminum and rubber</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>7 pounds</td>
<td>8.5 pounds</td>
<td>31 lbs</td>
</tr>
<tr>
<td><strong>Maximum Obstacle Height</strong></td>
<td>6 inches (1.3 * spoke length)</td>
<td>9 inches (2.25 * spoke length)</td>
<td>40 cm (15.7 in) (2.19 * spoke length)</td>
</tr>
<tr>
<td><strong>Maximum Speed</strong></td>
<td>4.9 feet per second (3 body lengths per second)</td>
<td>4.5 + feet per second (3+ body lengths per second)</td>
<td>3.5 feet per second (2+ body lengths per second)</td>
</tr>
<tr>
<td><strong>Body Joint</strong></td>
<td>None</td>
<td>Actuated with hobby servomotor</td>
<td>passively compliant, non-backdrivable, 60 W motor</td>
</tr>
<tr>
<td><strong>Motor</strong></td>
<td>Team Associated. Reedy MVP motor</td>
<td>90 Watt Maxon RE-35 DC motor</td>
<td>150 Watt Maxon DC motor</td>
</tr>
<tr>
<td><strong>Motor Controller</strong></td>
<td>Rooster reversible RC Speed controller</td>
<td>Daventech H-Bridge motor controller (0-50v, 20A max current)</td>
<td>Victor 885</td>
</tr>
<tr>
<td><strong>Transmission</strong></td>
<td>Custom spur gear transmission</td>
<td>26:1 integrated planetary gear transmission</td>
<td>96:1 final</td>
</tr>
<tr>
<td><strong>Drive Train</strong></td>
<td>Min-E-Pitch belt drive</td>
<td>0.1475 pitch chain and steel sprockets</td>
<td>.25 pitch chain</td>
</tr>
<tr>
<td><strong>Torsion Device</strong></td>
<td>Delrin with torsion spring</td>
<td>Aluminum with extension spring</td>
<td>aluminum with torsion spring</td>
</tr>
<tr>
<td><strong>User Interface</strong></td>
<td>2 Channel RC transmitter</td>
<td>3 Channel RC transmitter</td>
<td>7 channel RC PCM</td>
</tr>
<tr>
<td><strong>Power Supply</strong></td>
<td>7.2 volt NiCad battery pack</td>
<td>9.8 volt NiMh battery pack</td>
<td>18V drive and 7V logic and steering (2.5 lbs)</td>
</tr>
</tbody>
</table>
# APPENDIX B: SUMMARY OF WHEGS ROBOTS AND PRECURSORS

<table>
<thead>
<tr>
<th></th>
<th>Pruero</th>
<th>Rhex</th>
<th>Whegs I</th>
<th>Whegs II</th>
<th>Whegs III</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length</strong></td>
<td>7 inches?</td>
<td>6 inches?</td>
<td>19.5 inches</td>
<td>16.5 inches</td>
<td>36 inches</td>
</tr>
<tr>
<td><strong>Spoke Length</strong></td>
<td>7 inches?</td>
<td>6 inches?</td>
<td>4.5 inches</td>
<td>4 inches</td>
<td>6 inches</td>
</tr>
<tr>
<td><strong>Chassis Material</strong></td>
<td>Aluminum</td>
<td>Aluminum</td>
<td>Delrin</td>
<td>6061 aluminum</td>
<td>Carbon fiber and aluminum</td>
</tr>
<tr>
<td><strong>Steering Configuration</strong></td>
<td>Differential steering</td>
<td>Differential steering</td>
<td>Pushrod type, 530 degrees travel, 2 MHz, HSB-300 servos</td>
<td>Pushrod type, 530 degrees travel, 2 Fujiha S3000 servos</td>
<td>Pushrod type with rack and pinion, 330 degrees travel</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>7 pounds</td>
<td>7 pounds</td>
<td>14.3 pounds</td>
<td>?</td>
<td>8 inches?</td>
</tr>
<tr>
<td><strong>Maximum Obstacle Height</strong></td>
<td>6 inches (1.3” spoke length)</td>
<td>6 inches (1.3” spoke length)</td>
<td>9 inches (2.25” spoke length)</td>
<td>8 inches?</td>
<td>?</td>
</tr>
<tr>
<td><strong>Maximum Speed</strong></td>
<td>Slow?</td>
<td>?</td>
<td>4.5 feet per second (3 body lengths per second)</td>
<td>4.5 + feet per second (3+ body lengths per second)</td>
<td>?</td>
</tr>
<tr>
<td><strong>Body Joint</strong></td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Actuated with hobby servomotor</td>
<td>worm gear</td>
</tr>
<tr>
<td><strong>Problems</strong></td>
<td>Lots of motor weight, difficult to turn, body always laying on ground. Lots of motor weight tends to kick up debris, motor is always accelerating or decelerating the track</td>
<td>Poor construction, open chassis</td>
<td>Open chassis, body joint sometimes broke</td>
<td>Weak drive train, body joint failed due to impacts.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Agri Whegs</th>
<th>DAGSI Whegs</th>
<th>Climbing Mini Whegs</th>
<th>Lunar Whegs</th>
<th>USAR Whegs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length</strong></td>
<td>36 inches</td>
<td>36 inches</td>
<td>7 inches</td>
<td>19 inches</td>
<td>36 inches</td>
</tr>
<tr>
<td><strong>Spoke Length</strong></td>
<td>7.6 inches</td>
<td>7.5 inches</td>
<td>4 inches</td>
<td>7 inches</td>
<td>7 inches</td>
</tr>
<tr>
<td><strong>Chassis Material</strong></td>
<td>Aluminum</td>
<td>6061 Aluminum and carbon fiber</td>
<td>Delrin</td>
<td>Aluminum and carbon fiber and Delrin</td>
<td>Aluminum</td>
</tr>
<tr>
<td><strong>Steering Configuration</strong></td>
<td>Cable drive</td>
<td>direct drive servos with Ackerman constraint</td>
<td>None</td>
<td>Pushrod type with rack and pinion</td>
<td>Differential steering</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>33 lbs</td>
<td>31 lbs</td>
<td>8 ounces</td>
<td>24 lbs</td>
<td>3 lbs</td>
</tr>
<tr>
<td><strong>Maximum Obstacle Height</strong></td>
<td>9 inches</td>
<td>20 cm (7.87 in)</td>
<td>(2.19” spoke length)</td>
<td>indefinite</td>
<td>7 inches</td>
</tr>
<tr>
<td><strong>Maximum Speed</strong></td>
<td>3.5 feet per second (2+ body lengths per second)</td>
<td>3.65 feet per second (2+ body lengths per second)</td>
<td>?</td>
<td>1.5 body lengths per second</td>
<td>?</td>
</tr>
<tr>
<td><strong>Body Joint</strong></td>
<td>None (never completed)</td>
<td>pasively constrained, non-backdrivable, 60 W motor</td>
<td>two wheels, one at middle axle and one forward of the middle axle</td>
<td>Two hobby servos modified to continuously rotate</td>
<td>none</td>
</tr>
<tr>
<td><strong>Problems</strong></td>
<td>Body joint never worked, cable steering was problematic. Not seated against the elements.</td>
<td>First steering design not robust</td>
<td>body joint worked best when aligned with middle axle</td>
<td>Two hobby servos modified to continuously rotate</td>
<td>Differential steering may be problematic</td>
</tr>
</tbody>
</table>
APPENDIX C: SELECTED CALCULATIONS

Motor torque calculations.

Assume the lift required is the most in Figure 53. The middle wheel legs must lift the entire mass of the robot.

Mass = robot weight + Payload = 14 Kg + 4.5 Kg = 18.5 Kg

Wheel-leg length = moment arm = 0.19 meters

Ideal Stall Motor torque = m * g * l * 2
= 18.5Kg * 9.8 m/(s*s) * 0.19 * 2
= 69 Newton Meters.

(the factor of two was chosen such that the motor is only half way to stall torque during this lift).

Given this motor:
RE 40/E40 mm, Graphite Brushes, 150 Watt (#148866)

Stall Torque = 1.69 Newton meters at 12 V.
= 2 Newton meters at 16 V (estimate)

Stall Torque at wheel leg = motor torque * motor trans * motor trans eff. * drive trans * drive trans eff. * sprocket trans eff.
= 101 Newton Meters

101 Nm > 69 Nm. The motor will have plenty of torque to climb the obstacle.

Drive shaft design:
Assuming that stall conditions will occur, the front drive axle will experience 101 Nm of torque.

The maximum shear stress due to pure torsion in a round shaft is:

\[ \tau = \frac{16 \cdot T}{\pi \cdot d^3} \]

Let’s assume the maximum shear stress is equal to 0.58 the maximum normal stress (this is an excellent assumption when the object is in pure shear). The normal yield strength of 303 Stainless steel is =240 MPa, so the maximum shear stress is 139 MPa.

\[ d = \sqrt[3]{\frac{16 \cdot T}{\pi \cdot \tau}} \]

\[ d = 0.015 \text{ meters (0.6 inches)} \]
Body Joint stiffness Calculations:

Initially, I assumed that if the robot is suspended from one segment, then the weight of the other segment should cause the body joint to rotate 7 degrees (.12 rad), about half the range of motion in a given direction. This will cause an axial displacement of the worm equal to

\[0.12 \text{ rad} \times 0.93'' = 0.116''\]

where 0.93” is the radius of the driven worm.

At this displacement, the springs have to counter a torque caused by the front segment, approximated as 124 inch lbs. The force on the worm is:

\[124 \text{ inch lbs} \times 0.93'' = 130 \text{ lbs}\]

So the desired spring stiffness is:

\[K = \frac{\Delta F}{\Delta X} = \frac{130 \text{ lb}}{0.116''} = 1125 \text{ lb/in}\]

A single Bellville spring from McMaster Carr (#9712k21) has a stiffness of 15,625 lb/in. Stacking twenty of them gives an equivalent spring constant of 781 lb/in. This is lower than originally desired, however, the total maximum displacement of twenty springs is 0.32,” yielding a maximum force of 234 lbs, well above the 130 lbs caused by the passive weight of the robot. Experimentally, these springs rarely reached their maximum displacement.


Bernstein, C., Connolly, M., Gavrilash, M., Kucik, D., and Threatt, S., "Demonstration of Surf-Zone Crawlers: Results from AUV Fest 01," Surf Zone Crawler Group, Naval Surface Warfare Center, Panama City, FL (2001).


