A SMALL, INSECT-INSPIRED ROBOT THAT RUNS AND JUMPS

by

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Abstract

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Studies of insect locomotion, such as walking in cockroaches and jumping in froghoppers, provide inspiration for highly mobile small robots. This thesis describes several small vehicles called Mini-Whegs which incorporate abstracted insect locomotion principles to improve mobility over rough terrain and relatively large obstacles. The development of a robust, reliable, inexpensive, and lightweight Mini-Whegs platform paves the way for the most recent robot, Mini-Whegs 9J, which includes independent running and jumping capabilities. Mini-Whegs 9J can run at more than three body lengths per second and jump over or onto obstacles almost two body lengths tall.

Chapter 1 – Introduction

Small mobile robots are useful in a variety of applications. They can perform in hostile environments and outmaneuver larger vehicles in confined spaces. Small robots can be useful for covert or search and rescue operations. Large groups of small robots provide redundancy in exploration missions. Small mobile robots are also appropriate for insect inspired research.

Currently existing small robots are often limited in mobility due to external power supplies, excessive weight, or small wheels. The Center for Biologically Inspired Robotics Research (Biorobotics Lab) at Case Western Reserve University has already developed several small robots called Mini-Whegs which overcome some of these obstacles. The radio controlled robots can steer and run at speeds of more than eight body lengths per second. A prototype has also been built which incorporates a jumping mechanism into the robot at the expense of steering and control.

The purpose of this thesis is to describe the design process for creating a small robot that combines steering, control, and jumping elements into the same vehicle while incorporating inspiration from biological models for locomotion from the cockroach and froghopper.

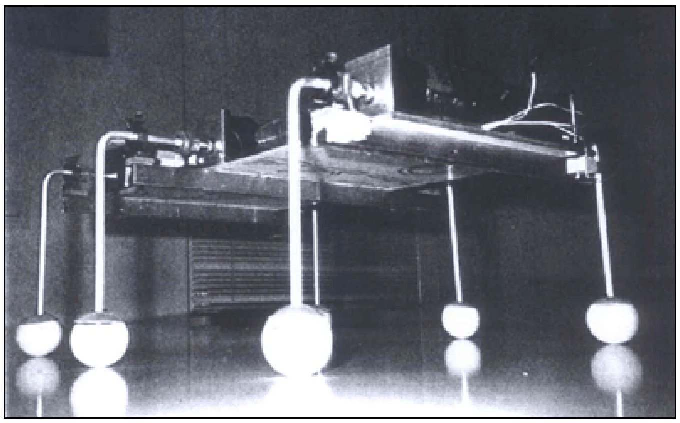


Figure 1.1 – Six motors drive the six L-shaped legs of PROLERO.

1.1 Whegs

Legs offer greater mobility than wheels over uneven surfaces. However, traditional legged robots require many actuators and are difficult to control. Some previous attempts have been made by research groups to create a simpler leg mechanism. For example, the European Space Agency's PROLERO (PROtotype of LEgged ROver) consists of six spokes driven in a circular arc by six individual motors (Figure 1.1) (Martin-Alvarez et al. 1996). RHex improves upon the basic PROLERO design (Saranli et al. 2000, 2001). It has passively compliant legs and a software control system that permits the operator to change its gaits. Roger Quinn of the Biorobotics Lab at Case took the combination of wheels and legs one step further, to create *whegs* (Quinn et al. 2001). In this paper, *wheg* will refer to the appendage, while *Whegs* and *Mini-Whegs* will refer to the robots which employ wheg appendages for locomotion. A wheg is a three-spoke appendage driven like a wheel at a central hub. The bare spokes allow a wheg to reach over larger obstacles than a wheel (Figure 1.2). The first robot to use whegs, Whegs I, used six whegs driven by a single motor (Figure 1.3). Neighboring pairs of whegs were offset by 60º to give the robot an alternating tripod gait, making it statically stable at any point in its stride.

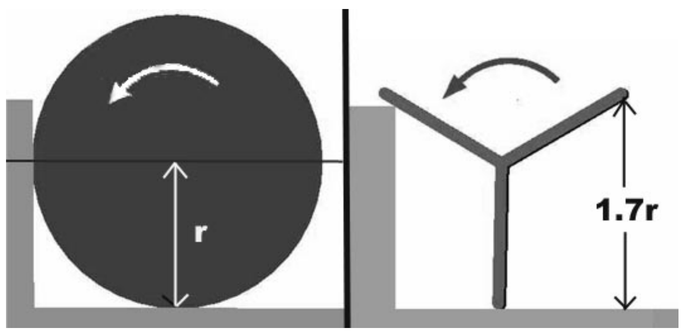


Figure 1.2 – Whegs can reach much higher than wheels to overcome obstacles.

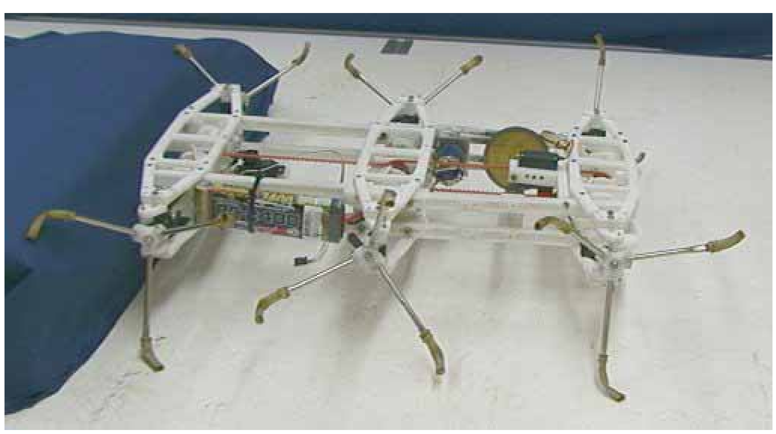
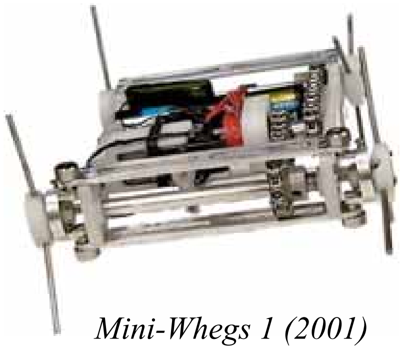


Figure 1.3 – Whegs I

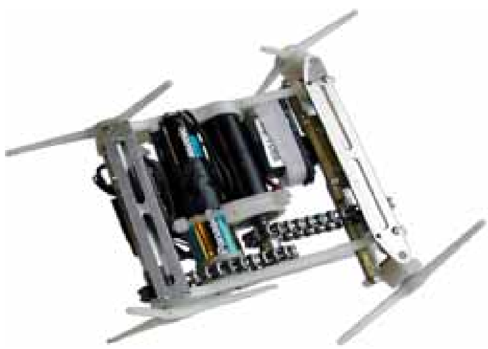
1.2 Mini-Whegs

Mini-Whegs demonstrates the scalability of the whegs concept. To reduce length and complexity, Mini-Whegs robots employ four whegs in an alternating diagonal gait. The four whegs are driven by a single central motor. Steering is accomplished with a servo driven rack and pinion design, similar to automotive steering. Mini-Whegs robots have been through several iterations (Figure 1.4).



Mini-Whegs 1 (2001)

Mini-Whegs 2 (2001)



Mini-Whegs 3 (2002)

Mini-Whegs 5 (2002)

Mini-Whegs 7 (2003)

Mini-Whegs 8 (2004)

Figure 1.4 – Overview of Mini-Whegs robots which do not include a jumping mechanism (not to scale).

Mini-Whegs 1 was a prototype to prove the scalability of the whegs concept. Mini-Whegs 2 was an early attempt at an even smaller robot. However, the small batteries used to power the central motor could not provide the electric current necessary to drive the motor. The tiny custom made components also made the robot difficult to assemble. Mini-Whegs 3 returned to the scale of Mini-Whegs 1. It was used as a platform for testing several steering joint mechanisms. Mini-Whegs 4J was a prototype to prove that a jumping mechanism could be added to a whegs platform to overcome larger obstacles. However, it did not include steering or radio control. Mini-Whegs 5 was built to test different foot designs and to create a more robust and reliable steering design. After Mini-Whegs 5, Mini-Whegs 6J was built to attempt to create a fully controllable jumping robot, combining the features of Mini-Whegs 4J and Mini-Whegs 5. However, this robot proved to be too heavy to operate effectively. The Mini-Whegs platform was reexamined to find a way to reduce weight and size, leading to the development and construction of Mini-Whegs 7. Concepts used in Mini-Whegs 7 were then incorporated in a more complete design called Mini-Whegs 8, and finally in a fully controlled jumping robot called Mini-Whegs 9J. An overview of all generations of Mini-Whegs can be seen in Figure 1.4 and Figure 1.5. See Appendix A for more detailed information about each robot.

Mini-Whegs 4J (2002)

Mini-Whegs 6J (2003)

Mini-Whegs 9J (2004)

Figure 1.5 – Evolution of jumping Mini-Whegs (not to scale).

1.3 Structure of the Thesis

The purpose of the work described in this thesis was to develop a fully controllable, small, jumping Whegs robot. Several intermediate robots were constructed to test concepts and to increase mobility or reduce size and weight.

The first three chapters of the thesis describe the inspiration and previous work on this project. First, this chapter discusses the need for small robots and explains the concept of whegs as developed by Quinn et al. Chapter 2 gives a more in-depth background of existing solutions for running and jumping in nature and in previous work on other robots. Insect research on cockroaches and jumping insects, like the froghopper, provides biological inspiration for the jumping whegs robot. In addition, existing jumping solutions in other robots are discussed. Chapter 3 describes the development of a prototype jumping Whegs platform. This prototype jumping Whegs robot, called Mini-Whegs 4J, cannot be steered and jumping is not independent of walking. However, it does work as a proof of concept for the incorporation of a jumping mechanism in a Mini-Whegs robot.

The next four chapters describe the design, construction, and testing of several small robots which lead to the final design. Chapter 4 discusses the design and improvements in several of the components of Mini-Whegs 5, focusing on a reliable steering design and on an effective design for the wheg appendages. The next chapter describes the first attempt at combining steering and radio control into a Mini-Whegs robot with independent running and jumping. The resulting robot, Mini-Whegs 6J, was too heavy and large to function properly, so further steps were necessary to create a successful design. Chapter 6 discusses the lighter, smaller, and cheaper robots, Mini-Whegs 7 and Mini-Whegs 8, designed to overcome the flaws of the first controllable jumping effort. In Chapter 7, the methods used to create the lighter, smaller robots are combined with successful components of the first jumping attempt to create the final robot, Mini-Whegs 9J.

Chapter 2 – Background and Inspiration

Small robots are excellent for fitting into tight spaces, moving about undetected or facing environments too dangerous for humans. However, most environments in which robots are expected to perform contain many obstacles to mobility. Obstacles as small as a stair or a rock, which would be quite easy for a human to step over, can stop a small wheeled or tracked robot. Therefore, it is useful to examine other modes of locomotion to improve robot mobility.

2.1 Biological Inspiration

Insects are extremely mobile creatures. They exist in almost every environment known to man. They can run, climb, jump, swim, and even fly. The success with which insects move about their environments forms an excellent source of inspiration for the development of small mobile robots.

2.1.1 Cockroach walking

Cockroaches make an excellent subject for biological research because they are large enough to observe and experiment with easily. The products of millions of years of evolutionary fine tuning, cockroaches run quickly and easily surmount obstacles in their paths. By examining the mechanisms these insects use for locomotion, effective robotic vehicles can be designed.

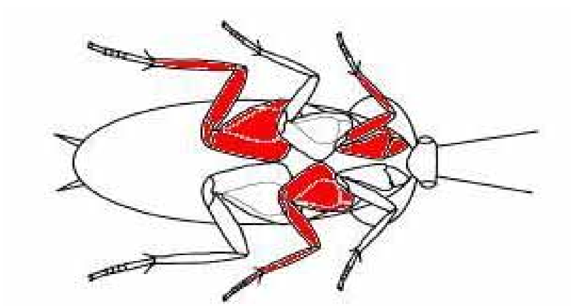


Figure 2.1 – The cockroach walks in an alternating tripod gait. The highlighted legs move together.

The death head cockroach nominally walks in a tripod gait (Wilson, 1966). The animal's front and rear legs on one side move in unison with the middle leg on the opposite side of its body. At least three legs remain in contact with the ground at all times, forming a statically stable tripod (Figure 2.1).

One of the primary problems encountered when designing a legged vehicle that is propelled by electric motors is that the power to weight ratio of motors is poor relative to muscles. Furthermore, this ratio decreases with the size of the motors. Whegs solves this problem by using only one motor to propel all six legs. Using this strategy its actuator system has a 50% greater power to weight ratio than RHex (Quinn et al. 2003). iSprawl, developed at Stanford University, is a new hexapod robot that uses this same strategy (Kim et al, 2004). A motor drives a dual crank slider mechanism to convert rotary to linear motion. The linear motion of the slider is transmitted to the legs of the robot via cables sliding inside flexible tubes (Figure 2.2). Each cable pulls or pushes the feet of the robot up or down. By fastening the front and rear cables of one side with the middle cable from the other side of the robot to the same crank slider mechanism, a tripod is formed. The second crank slider turns 180º out of phase from the first, completing the alternating tripod gait. The 15.5cm long robot can move over 15 body lengths per second (2.3m/s).

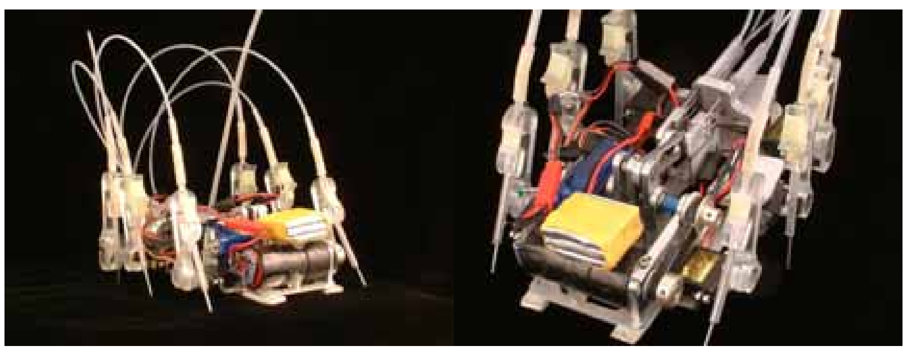


Figure 2.2 – iSprawl has six legs, each driven by a flexible cable, to create an alternating tripod gait.

When running in a tripod gait, the front legs of the cockroach swing as high as its head, allowing the insect to climb over irregular terrain without changing its gait. This allows the cockroach to traverse irregular terrain without significant gait changes (Full and Tu, 1991). However, when larger obstacles are encountered, the animal changes its gait. The front legs move together to reach onto an obstacle before climbing it (Figure

2.3). The middle legs are also used to push the front of the body upwards to allow the insect to climb over the barrier (Watson, et al. 2002).

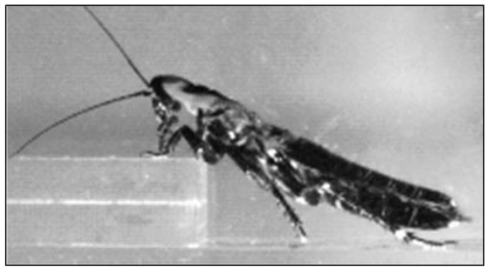


Figure 2.3 – The cockroach uses each pair of legs in unison to overcome an obstacle.

The mobility principles which allow the cockroach to navigate difficult terrain are incorporated in Whegs II (Allen, 2004). A single motor drives six wheg appendages via a chain and sprocket drive train in this 47cm long robot. As mentioned in Chapter 1, the three-spoke design of the whegs creates a high reach, even higher relative to the body than a cockroach's reach. As in other Whegs robots, the whegs are initially offset to create a nominal alternating tripod gait.

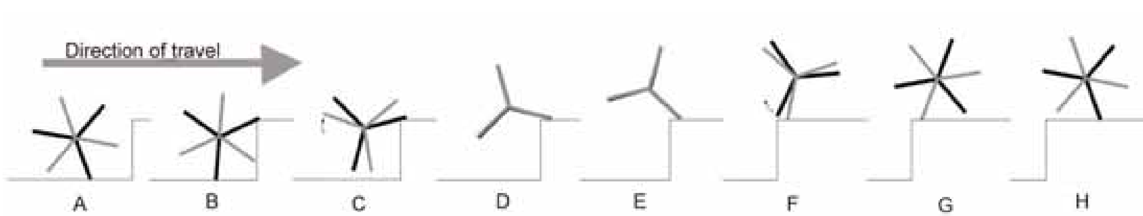


Figure 2.4 – Torsionally compliant elements allow pairs of whegs to operate in phase to overcome large obstacles. The black wheg is on the left side of the robot, while the gray wheg is on the right. As the robot approaches the step (A), the whegs are offset by 60° to create the normal tripod gait. The obstacle forces the whegs into phase (B-C) so they can work together to

climb onto the obstacle (D-E). After the obstacle is cleared, the torsion springs pull the whegs back to the normal offset (F-H).

When an obstacle is encountered, torsionally compliant mechanisms between the axle and each wheg allow the wheg to rotate up to 60º. Thus, the offset between neighboring whegs is eliminated so that the appendages can move in unison to overcome an obstacle (Figure 2.4). In addition to the torsionally compliant devices, a body joint along the same axis as the middle wheg axle of the robot allows the front of the robot to be tilted upwards to increase the reach of the front whegs even further (Figure 2.5). Using both the abstracted biological principals of gait change and body flexion, Whegs II is able to overcome obstacles 23cm high with whegs measuring only 20cm in diameter.

Figure 2.5 – Whegs II incorporates a body joint for increased mobility.

2.1.2 Froghopper jumping

Many insects jump to escape from predators, to increase their speed across land, or to launch into flight. Some insects, like bush crickets, have long rear legs which provide leverage which enable them to jump longer distances than insects of comparable mass with shorter legs (Burrows and Morris, 2002). The froghopper, *Philaenus* *spumarius*, on the other hand, has relatively short legs, but can outperform any other jumping insect relative to its body length. This unique insect has highly specialized rear legs which the animal simply drags behind it while walking. Before a jump, the froghopper rotates its rear legs forward until they are parallel with the body, with the femora tucked between the middle legs and the body. The tibiae fold back until they are also parallel with the body. A ridge on each femur engages with a protrusion on the coxa, locking the femur in place. The muscle which powers the jump can then slowly contract while the leg remains immobile. When enough energy is stored in the muscle, the femur disengages from the coxa, snapping quickly outward with a force 414 times the body weight of the insect. The release of the leg during jumping occurs within 1ms (Figure 2.6) (Burrows, 2003).

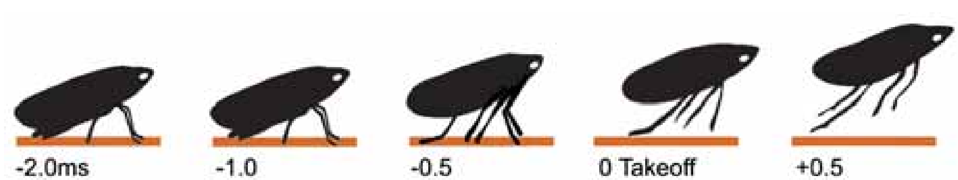


Figure 2.6 – The froghopper contracts its jumping muscles and then leaps within 1ms.

Like the froghopper, the jumping Mini-Whegs robots discussed in this thesis use four legs for locomotion with an additional set of legs specialized for jumping. The jumping legs retract slowly until enough energy for a jump has been stored, at which point the legs can extend suddenly to complete the jump.

2.2 Other Jumping Robots

Besides examining biological methods for jumping, several methods have been developed in other robots to overcome large obstacles. Some of these robots use jumping or hopping as a primary mode of locomotion, while others use jumping as an option when the primary mobility method is not sufficient to surmount an obstacle.

2.2.1 Scout

Scout, a small robot developed at the University of Minnesota, is a good example of a small robot that can jump to overcome obstacles in its path (Stoeter et al. 2002). Scout is a cylindrical robot 4.0cm in diameter and 11.0cm long. Wheels at either end of the cylinder provide the primary method of locomotion. A triangular spring-steel foot between the wheels stabilizes the robot during normal rolling. When an obstacle is encountered, a winch inside the cylindrical body draws the foot against the side of the robot. When the winch releases suddenly, the spring steel foot straightens and impacts the ground, causing the robot to jump up to 20 cm high. The combination of rolling and jumping locomotion makes Scout well suited for environments with flat surfaces interrupted by stairs, such as the inside of a building (Figure 2.7). However, the low ground clearance while rolling makes navigation over rough terrain difficult for the robot.

Figure 2.7 – Scout includes a triangular spring steel jumping foot which allows it to jump up stairs.

2.2.2 Hopper

Sandia National Laboratory's Intelligent Systems and Robotics Center (ISRC) has developed a robot called *Hopper*, which uses jumping as its only mode of locomotion (Sandia 2000). The robot, about the size of a coffee can, has a weighted, rounded bottom so that it rights itself after each jump (Figure 2.8). A gimbaled system inside the robot slightly offsets the weighting to direct the robot's next jump in a desired direction. A gasoline powered piston fires and strikes the ground to make the robot jump 3m to 6m high. The Hopper can jump again in as little as 5 seconds.

Figure 2.8 – The Hopper can leap up to 6 meters high using a gasoline combustion powered piston.

2.2.3 Frogbot

Like Hopper, *Frogbot*, developed by NASA's Jet Propulsion Laboratory and the California Institute of Technology, uses a single foot to jump from location to location (NASA 2000). The 40cm tall Frogbot consists of an aluminum frame which acts as a leg. The leg bends at a spring-loaded knee (Figure 2.9). A single motor stores energy in the spring as it causes the knee to bend. When the motor releases the spring, the robot jumps up to 1.8m high. Since the robot falls over when it lands, plastic levers are deployed to right the Frogbot after every hop.

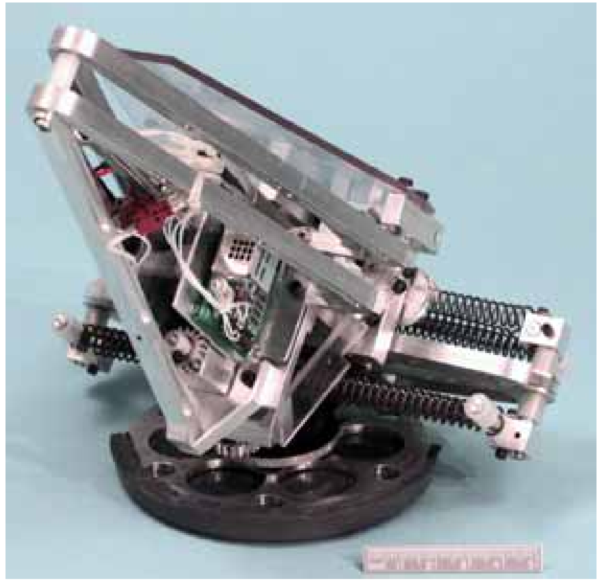


Figure 2.9 – Stiff springs contract quickly to extend the bent leg of Froghopper.

2.2.4 Bow Leg

Carnegie Mellon's *3D Bow Leg Hopper*, is a third vehicle which uses a single leg to move (Zeglin and Brown, 2002). A string pulls on the end of the fiberglass leg, causing it to bend like an archer's bow. The angle of the leg relative to the body is adjusted by servos via two other control strings to direct the jump (Figure 2.10). Releasing the main string straightens the bow leg, and allows the robot to jump up to 50cm.

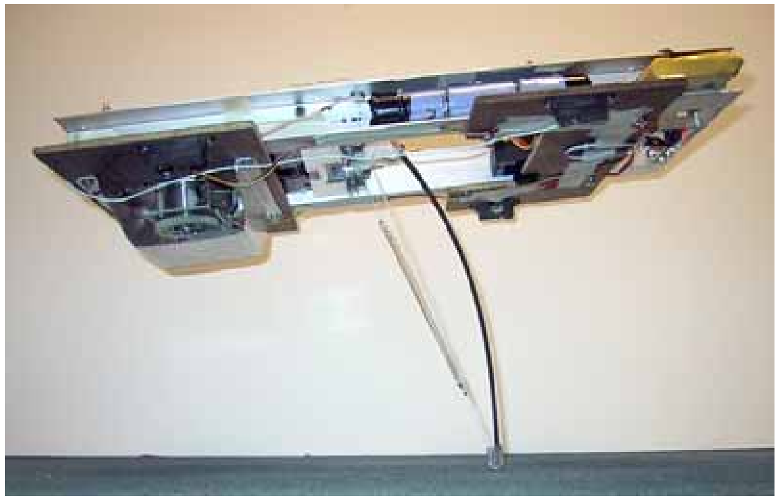


Figure 2.10 – A single flexible fiberglass leg adjusted by control strings forms the propulsion method for the 3D Bow Leg Hopper.

2.2.5 Flip'n Fido

Toys can provide an inexpensive example of jumping vehicles as well. The Gemmy Industries Corporation's *Flip'n Fido* is a 10cm long dog-shaped vehicle which walks and does back-flips several centimeters high. An inexpensive motor drives an extensive gear reduction ending in a cam. The cam is part of a mechanical linkage which moves the legs of the robot and stretches a stiff spring (Figure 2.11). The front legs of the vehicle move in unison, as do the rear legs. After several shuffling steps, the rear legs retract against the bottom of the body, stretching the spring. When the legs are fully retracted, the legs spring back, sending the toy into a flip.

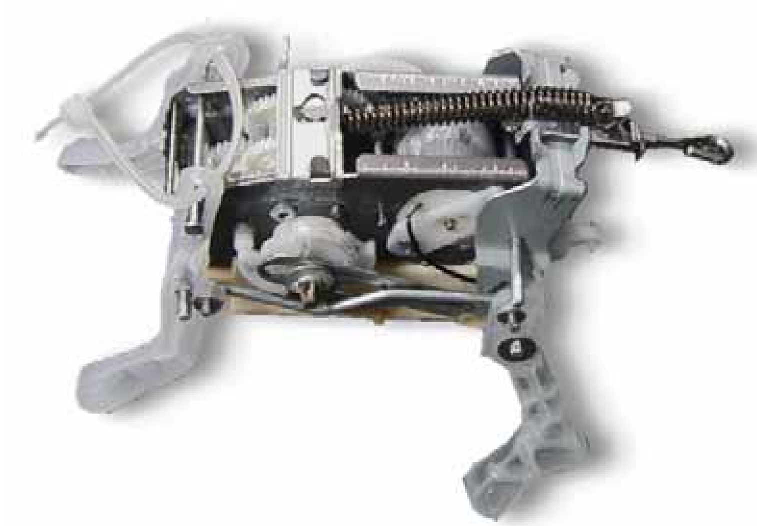


Figure 2.11 – A stiff spring stores energy created through an extensive gear train in the Flip'n Fido toy.

2.3 Jumping Concepts for Mini-Whegs

Several solutions for creating a jumping mechanism in a robot have been developed, some better suited towards integration in a Mini-Whegs platform than others were. The mechanism must release enough energy to provide a 15cm to 20cm vertical leap. The mechanism should be compact so that it does not interfere with the normal wheg locomotion. A mechanical energy storage method is desired for repeatable jumping, as a spring does not require refueling to operate a second time. Ultimately, three different spring types were considered: a flat bending spring, a torsion spring, and a linear spring (Morrey 2003).

2.3.1 Scorpion

Operation of Mini-Whegs 3 showed that the high torque Maxon motor was easily capable of flipping the robot upside down. Since Mini-Whegs is equally mobile upright or upside down, a jumping mechanism design was considered which would be stored on the top of the robot. When a jump was desired, the robot would flip over by driving into the obstacle. This would bring the jumping mechanism to the bottom of the robot, where it could be released to complete a jump.

Figure 2.12 – The Scorpion jumping concept retracted on top of the robot before a jump (left), and then released from the bottom of the robot (right).

The *Scorpion* jumping mechanism consists of a long piece of spring steel bent over the top of the robot in a configuration similar to the tail of a scorpion, held in place by a cable on a winch. When flipped over, the cable is released, allowing the steel to straighten and impact the ground (Figure 2.12), similar to the operation of the spring steel foot on the Scout robots. While the design was successful in creating high, predictable leaps on a Mini-Whegs mockup, the Scorpion design was ultimately eliminated for its large size relative to the robot. The large piece of spring steel dramatically increases the height of the robot and eliminates room for the addition of other components, such as electronics.

2.3.2 Mousetrap

Experimentation showed that the torsion springs which cause a mousetrap to snap closed stored more than enough energy to create a jumping motion. A torsion spring was fixed to the bottom of a Mini-Whegs mockup, with the free arm of the spring attached to a lever arm which impacts the ground to make the robot jump (Figure 2.13). Unfortunately, the design caused the mockup to flip excessively in the air. The simple wire lever arm was difficult to control, making jumps inconsistent.

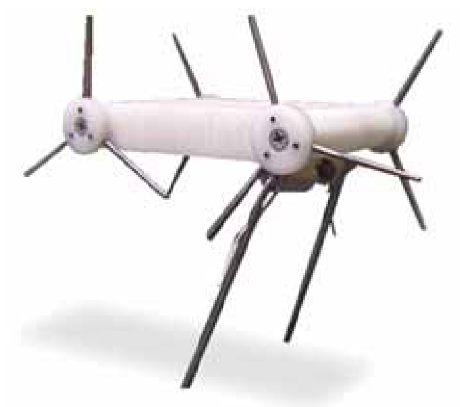


Figure 2.13 – The Mousetrap jumping concept in action.

2.3.3 Four-bar

The *Four-bar* mechanism which was finally adopted in the first jumping Mini-Whegs prototype is a progression of the Mousetrap design. The mechanism consists of a parallel four-bar linkage which fits between the wheg axles of the robot. The four-bar design makes the motion of the jumping legs during a jump much more predictable than the slender legs of the Mousetrap concept. A physical stop in the rotation is easily achieved to reduce rewinding time after a jump. Energy is stored in a linear extension spring which stretches from extensions of the jumping legs across the top of the robot (Figure 2.14). As the four-bar mechanism is retracted against the bottom of the body of the robot, the spring stretches. When the mechanism is released, the spring contracts quickly, pulling the extension of the jumping legs with it. As the leg pivots about an axle, it pushes a small foot toward the ground, which impacts and sends the mockup into the air.

Figure 2.14 – The Four-bar jumping mechanism is powered by a linear extension spring on top of the robot.

2.4 Discussion

The success of the Four-bar design led to its integration in a complete Mini-Whegs prototype, discussed in the next chapter. The resulting design, especially including the manner in which the mechanism is slowly retracted and suddenly released, imitates the manner in which a froghopper insect jumps. The resulting robot incorporates a functional jumping mechanism without eliminating any of the cockroach-inspired mobility of whegs.

Chapter 3 – A Jumping Prototype

To prove that a jumping ability could be successfully added to a Mini-Whegs platform, Mini-Whegs 4J was designed and built by Jeremy Morrey (Morrey 2003). This working prototype has jumped to heights exceeding 20cm, so it can easily jump onto a standard stair. The robot uses a single motor to drive both running and jumping. The jumping mechanism is loaded and released automatically while the robot runs. As the robot runs forward, the mechanism slowly retracts, then releases, and repeats.

3.1 Design

Mini-Whegs 4J is similar in design to other Mini-Whegs designs. Steering and control were unnecessary to prove the jumping concept, so components related to these functions were eliminated to save space and weight. The chassis of the robot is similar to the chassis of Mini-Whegs 3, with the addition of several mounting holes for the jumping mechanism.

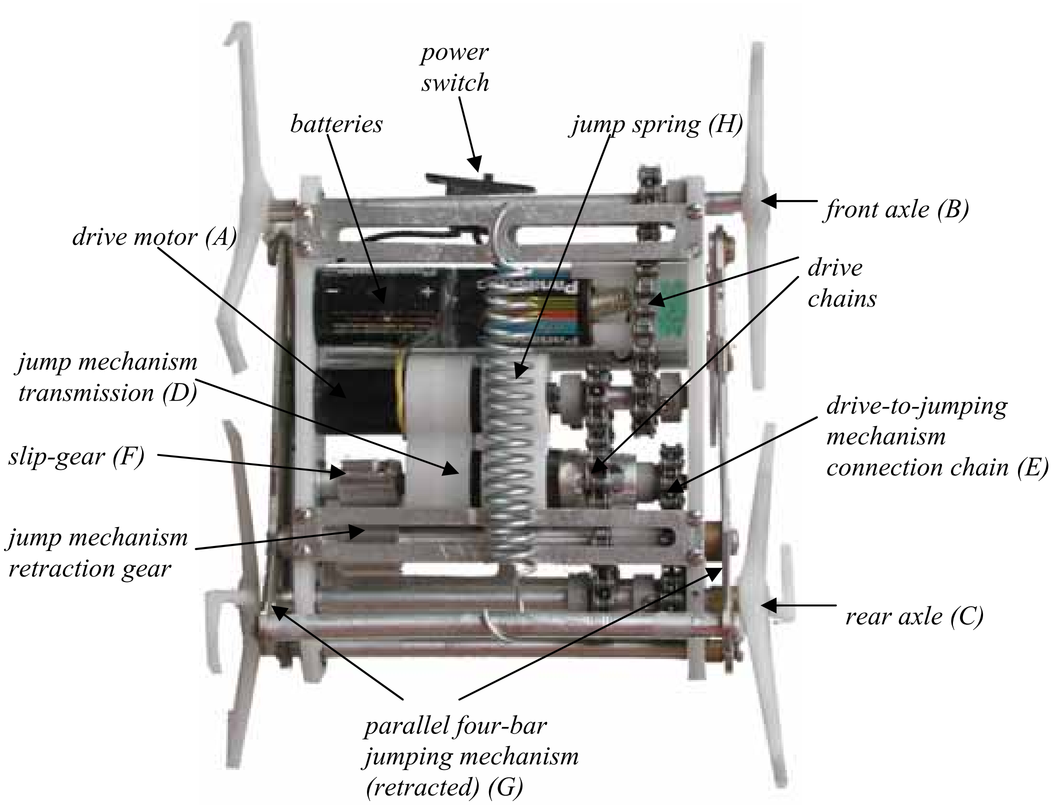


Figure 3.1 – Top view of Mini-Whegs 4J showing the location of important components. The front of the robot is at the top of the figure.

Figure 3.1 shows the layout of the jumping prototype with several key components labeled. The 1.2W RE-13 Maxon motor (A) used in Mini-Whegs 3 is again used to drive the whegs at the front (B) and rear (C) axles. A secondary transmission (D) is driven by a chain (E) between the wheg axle and the custom-built input to the transmission. A "slip-gear" (F) transmits power from the jumping transmission to an axle rigidly connected to the parallel four-bar jumping mechanism (G). Energy for each jump is stored in a linear spring (H), which stretches across the top of the vehicle. Figure 3.2 more clearly shows the four-bar jumping mechanism and spring attachment.

Figure 3.2 – Side view of Mini-Whegs 4J with elements of the jumping mechanism labeled.

3.1.1 Chassis Modifications

The chassis of Mini-Whegs 4J is based on the chassis of Mini-Whegs 3. Extra carefully spaced mounting holes for the jump axles were added, taking into consideration the finite increments allowed between chain sprockets without requiring additional tensioners. Components were placed as close together as possible without interference to minimize the weight of the robot. The resulting chassis measures 9.4cm long by 7.6cm wide, about 1cm longer and 1.3cm wider than Mini-Whegs 3.

3.1.2 Control System

Since Mini-Whegs 4J was a prototype to demonstrate the successful integration of a jumping mechanism with a Mini-Whegs platform, radio control was eliminated. Two 3 Volt CR2 batteries in series are directly connected to the drive motor with a small switch. When the switch is turned on, the motor drives both wheg axles, while the rear wheg axle drives the secondary transmission for the jumping mechanism. Thus, the robot runs as the mechanism retracts, jumps, and repeats until it is turned off.

3.2 Implementing the four-bar jumping mechanism

Realizing the jumping mechanism selected for the robot required selecting a repeatable energy storage device to make multiple jumps possible. The desired jump trajectory is upwards and forwards so that the robot can jump onto a standard stair step. Keeping in line with the other Mini-Whegs robots, the design must be simple and robust, small and light. The jumping mechanism should integrate well with the regular Mini-Whegs chassis, requiring as few design changes as possible.

3.2.1 Mechanism activation

The selected four-bar jumping mechanism has only one degree of freedom, so theoretically, only one actuator is necessary to retract and release the linkage. In order to allow the stored energy for each jump to be stored in a repeatable device and in order for that energy to be released very quickly, a spring was selected as the means for energy storage. Several electromechanical methods for stretching or contracting a spring were examined, including use of a servo, solenoid, winch, or cam. Criteria for selection of the final method used included a good power to weight ratio, large range of motion, small size, and good repeatability. The design which proved to be most feasible was a mechanical “slip-gear”.

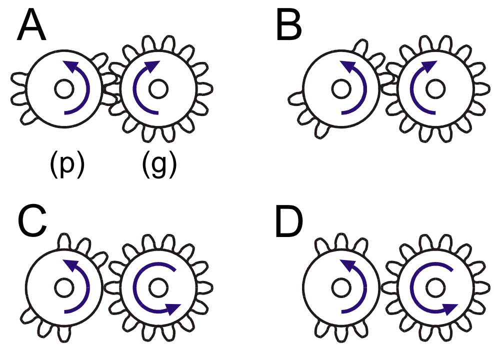


Figure 3.3 – The slip-gear consists of a pinion (p) with several teeth removed, and an unmodified gear (g). While the teeth are engaged (A-B), the jumping mechanism retracts, "winding up' the spring. When the teeth become disengaged, energy stored in a spring causes the gear to rotate quickly (C-D) in the opposite direction of winding.

The slip-gear consists of a pinion with several teeth removed driving a second unmodified gear attached to one joint on the four-bar mechanism. In Mini-Whegs 4J, the pinion and full gear are both 32 pitch, 14 teeth gears. The pinion has 8 teeth removed, leaving two sections of 3 teeth on opposite sides of the pinion. Figure 3.3 demonstrates how the slip-gear works. As the pinion rotates, its teeth engage with the gear (A) rigidly attached to the four-bar. This rotates the mechanism up towards the body of the robot just long enough to stretch the spring to its fully extended position, or about 100° of rotation. The pinion continues to rotate (B) until none of the teeth are engaged with the gear (C). At this point, the gear is free to rotate independently of the pinion (D), so the spring retracts suddenly, opening the jumping mechanism to its unloaded position and causes the robot to jump. As the pinion rotates even further, the teeth reengage, rewinding the mechanism for the next jump (A). Since the pinion has two separate sets of teeth, the jumping mechanism retracts and releases twice per revolution of the pinion.

This system requires no active input for control; it can simply wind and jump repeatedly. This is sufficient for Mini-Whegs 4J, since it is simply a demonstration vehicle for jumping integration.

Figure 3.4 – Custom components for the jumping transmission in Mini-Whegs 4J: (clockwise from nickel shown for scale) Maxon 275:1 planetary transmission, custom shaft housing, custom input shaft, clip to hold shaft in place, input gear for transmission.

Stretching a spring stiff enough to cause the robot to jump requires more torque at the slip-gear pinion than can be provided by the Maxon motor and transmission used for driving the whegs appendages, so an additional gear reduction was necessary. A secondary 275:1 metal gear planetary transmission was selected to achieve a total gear reduction of 18,545:1. The slip-gear pinion is directly mounted on the output shaft of the transmission. Since the transmission is normally mounted directly onto the motor, a custom housing had to be fabricated to allow an input shaft to be added (Figure 3.4). This input shaft is driven by the rear wheg axle of the robot via a chain and sprocket connection.

3.2.2 Geometry and materials

Bending in the long aluminum legs of the mockup jumping mechanism was noticed after extensive testing. Keeping clearance between the sides of the robot and the whegs to a minimum eliminated the option to add more material to the legs to strengthen them. Instead, titanium was chosen for the legs of the linkage for its strength to weight properties. The feet and other components can still be made from aluminum since they are experience lower bending loads.

To synchronize the motion between left and right legs and to strengthen the mechanism laterally, three shafts connect the sides of the robot at the joints of the mechanism. No cross-brace shaft can be mounted at the front of the jump feet since these joints must slide along the side of the robot in order for the mechanism to retract close to the body. Instead, an additional shaft at the top of the mechanism braces the sides while doubling as a mount for the spring. The shafts at the top two joints double as axles rotating in precision ball-bearings. The front-most axle is larger in diameter and is driven by the slip-gear transmission. Flats on the ends of the axle allow it to drive the legs of the four-bar linkage without slipping.

The legs of the mechanism are designed to be as long as possible without interfering with the front wheg axle of the robot. This creates the longest lever arm for jumping and allows the jumping feet to impact the ground below the center of gravity of the robot (Figure 3.5). The feet are oriented 20° below horizontal to make the robot jump upward and forward. Sharp points on the end of the feet ensure good traction during jumping.

Figure 3.5 – Photographs illustrating the motion of the four-bar mechanism during a jump.

In the original four bar design, the rearmost axle was driven, which avoids transmitting force through the un-braced joints at the front of the jump feet. However, space considerations in the robot do not allow the rear jumping axle to be driven. So, a strong joint is needed at the front of the jump feet. There is no room for a ball bearing, so a small brass bushing was used. A small hub protrudes from the feet. The bushing fits around this protrusion, which then fits into an appropriately sized hole in the jump leg.

The leg is held in place by a short screw, with a Teflon washer separating the screw head from the leg.

3.3 Spring selection

The more energy stored in the spring for a given input force, the higher the robot will be able to jump. Thus, an important consideration in the selection of a spring to store energy for jumping is that the spring be preloaded, that is, it should always be partially stretched. The energy stored in the spring which can be released during jumping is equal to the work done in stretching the spring, that is, the area under the force-displacement curve between the minimum and maximum stretch positions. For the same maximum force available to wind the spring, a softer, preloaded spring will be able to store more energy than a stiffer spring with no preload. Theoretically, a spring of infinitesimal stiffness with infinite preload would have a completely flat force-displacement curve, allowing it to store twice the energy of a stiff spring with no preload. However, the limited length of the robot does not allow for infinite springs, so a compromise must be made between spring length and stiffness.

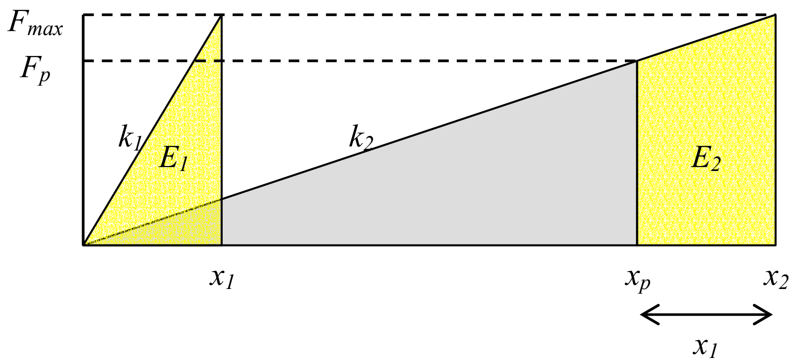


Figure 3.6 – A softer (k_2) spring with a preload (x_p) stores (2 – k_2/k_1) times more energy than a stiff spring (k_1) for the same displacement (x_1) and maximum force (F_{max}).

Figure 3.6 shows the relationship between preload of soft springs and energy storage. Consider two linear springs, one of high stiffness k_1, and a softer spring of stiffness k_2. Suppose the motor available can stretch spring 1 from its free length to a displacement x by exerting a force $F_{max}=k_1x_1$. The same force can stretch spring 2 to a displacement x_2 where $F_{max}=k_2x_2$. However, when the force from the motor is removed, the spring can only move a maximum distance x because of the geometry of the system. Thus, after the mechanism is released, spring 1 will return to its free length, but spring 2 will return to a displacement $x_p = x_2–x_1$. The "preload" for the displacement x_p is $F_p = k_2x_p$. With all the forces known, the energy released during a jump can be measured. The energy will be equal to the difference of the energy required to stretch the spring to its maximum displacement and the energy left in the spring after the jump. For the first spring, the energy released is $E_1 = ½F_{max}x_1 = ½k_1x_1^2$. For the second spring, the energy is $E_2 = ½F_{max}x_2 – ½F_px_p = ½k_2(2x_2x_1 – x_1^2)$. Since F_{max} is the same for both springs, $k_1x_1 = k_2x_2$, so $x_2 = k_1/k_2\, x_1$. Thus, $E_2 = ½(2k_1–k_2)\, x_1^2$. The ratio, $R = E_2/E_1$, of the energy released in the second spring to the energy released in the first spring is $R = (2 - k_2/k_1)$. Clearly, the smaller k_2, i.e. the softer the preloaded spring, the more energy it can store. For an infinitesimally stiff spring ($k_2 \rightarrow 0$), $R \rightarrow 2$, so twice as much energy can be stored in the spring. Unfortunately, a very soft spring must also have a very long preload displacement ($x_p = x_2 - x_1 = F_{max}/k_2 - x_1$), so a compromise must be made between length and stiffness.

The final spring was chosen experimentally from a selection of springs of different lengths and stiffness with the previously described considerations in mind. The spring cannot be too small, or the forces encountered will cause it to deform permanently. It must also be stiff enough to cause the robot to jump to the desired height. After testing several springs at different positions on the robot, a spring with a stiffness of about 0.5 N/mm was selected. This spring resulted in the highest jumping of all the springs tested.

3.4 Discussion

Mini-Whegs 4J successfully proves that a jumping capability can be added to a small robot to improve mobility and conquer obstacles of relatively large size. The robot can leap over 20cm high, easily jumping onto a standard stair (Figure 3.7). While the robot runs, energy is slowly stored in a spring. It takes about one minute to fully retract the jumping mechanism.

Figure 3.7 – Composite of video frames showing Mini-Whegs 4J jumping up a 15cm stair.

The four-bar jumping mechanism allows performance with a variety of spring sizes, varying stiffness, and different preloads to be characterized. Experimenting shows that a moderately stiff spring with a significant amount of preload works best. Softer springs with more preload tend to deform plastically, while stiffer springs cannot store as much energy.

Mini-Whegs 4J can run both upright and upside down, so the orientation after landing from a jump is unimportant. However, the robot can only jump when upright. This is not a problem since, with the jumping mechanism retracted, the robot can easily flip over like other Mini-Whegs robots by running into a large obstacle. There is sufficient torque available to cause the front of the robot to climb an obstacle until the whole robot flips over.

The lack of a control system makes Mini-Whegs 4J unsuitable as a platform for other research, such as sensor integration. It is simply a demonstration of running and jumping powered by the same motor. For independent and controllable operation to be achieved, jumping and running need to be separated. This separation was first attempted in Mini-Whegs 6J, discussed in Chapter 5. Before Mini-Whegs 6J was built, several design changes were made to the steering mechanism and wheg appendages to improve the mobility of running in the Mini-Whegs platform. These changes, discussed in the next chapter, were first integrated in Mini-Whegs 5.

Chapter 4 – Development of Reliable Components

Before creating a completely controllable robot with independent running and jumping modes of locomotion, further development of the steering mechanism and wheg appendages was needed to create a reliable Mini-Whegs platform. These changers were made in order to create a robot robust enough to withstand repeated impacts from jumping, falling, and running. Steering mechanisms in Mini-Whegs 1, 2, and 3 were subject to failure after relatively few cycles due to the weak springs and flexible materials used in their construction. The first several Mini-Whegs robots also had pointed feet at the end of the whegs, making maneuverability difficult on hard surfaces with little traction. They also caught easily on rough or tangled surfaces, causing the robot to flip or somersault. Several design changes, described in the following sections, were made to improve the performance of both the steering and appendage elements.

4.1 Steering mechanisms

In order to navigate around obstacles to travel from one location to another, Mini-Whegs robots need to have some sort of steering mechanism. The offset between neighboring appendages must be maintained for smooth walking, so skid steering—where the legs on one side of the robot simply move faster than the other side—is not an option. Thus, some mechanical linkage is required to pivot the whegs relative to the body of the robot, or to change the angle between the axles through a body joint.

All of the whegs on the robot must be powered. Thus, a mechanism is required which can transfer rotation through a pivot without seriously affecting the offsets between the whegs. A tight turning radius is desirable for improved maneuverability, so a large range of motion in the steering mechanism is also required.

4.1.1 Rack and Pinion Steering

Pivoting the whegs themselves instead of using a body joint is a more compact and easier to control solution. Since only the whegs instead of a whole section of the body must rotate, less torque, and hence a smaller servo, is necessary to steer the robot. Also, the drive train does not need to be in the center of the robot, which frees up space for other components and results in a more efficient layout.

The first Mini-Whegs robot includes a small servo which moves a rod side to side through the chassis via a small arm. The ends of the rod contain pins which fit into slots on the steering uprights. Thus, when the rod moves, the pin pulls the upright to one side or the other. All the robots designed after Mini-Whegs 1 use a rack and pinion system instead. A small pinion on the servo drives a gear rack instead of a simple rod. The connection to the uprights remains the same.

Mini-Whegs 2, Mini-Whegs 3, and Mini-Whegs 5 (Figure 4.1) all use a 64 pitch brass rack and pinion. This gives precise control over steering mechanism position. However, the brass components are heavy, and the small teeth easily disengage if the servo mount bends out of place by even a small amount.

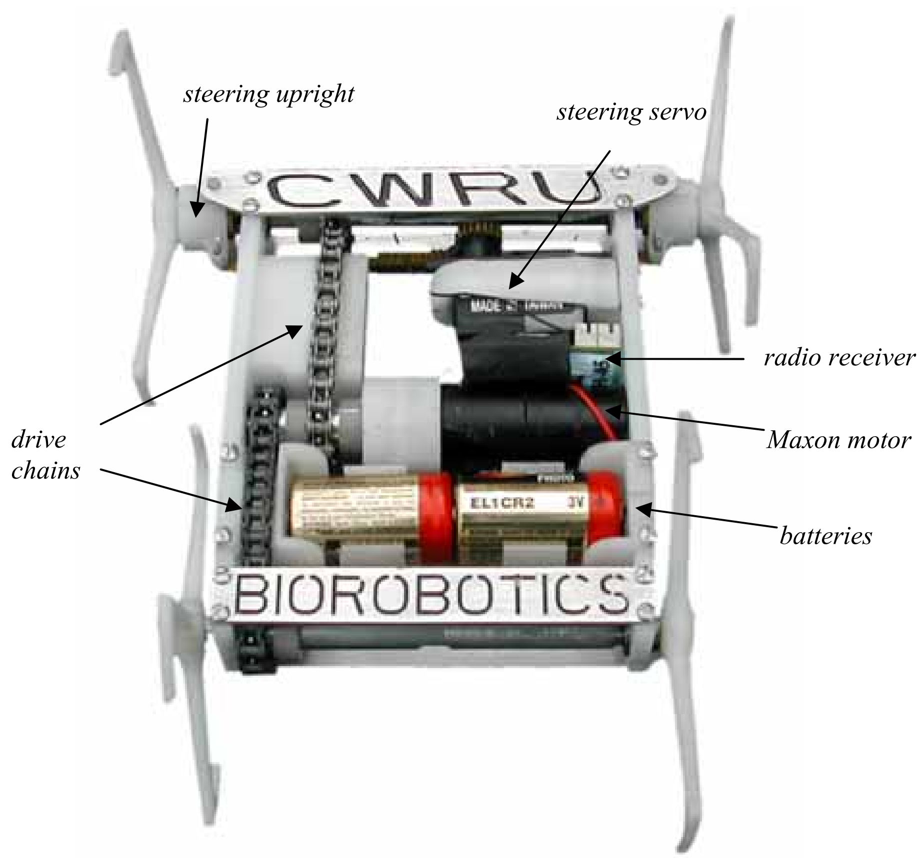


Figure 4.1 – Top view of Mini-Whegs 5 showing the layout of components.

A nylon rack was chosen for Mini-Whegs 6 and subsequent robots, primarily to reduce weight. The 48 pitch gear rack and pinions chosen have larger teeth than the brass parts, so they are also less likely to disengage. Since nylon is much more flexible than brass, there was a possibility for the rack to bend out of engagement with the pinion on the servo. However, by strategically placing support posts underneath the rack and holding the servo down with a small piece of foam, these problems are entirely avoided.

The combination of larger teeth and an improved mounting system leads to a much more reliable steering solution than with the brass rack. The weight reduction of 5g (87%) in the rack alone also creates an opportunity to carry a greater payload with the same robot.

4.1.2 Simplified Universal Joint

In order to transfer power from the driven axle to the whegs on the steering uprights, a small joint is required. Two intersecting degrees of freedom are required to allow the axle to rotate while it pivots to steer.

The first solutions for a small joint involve a flexible shaft. The ends of the driven axle on Mini-Whegs 1 are attached to a short length of spring tubing. The spring is attached to a small hub which rotates in the steering upright and attaches to the wheg. The spring has the advantage of adding some torsional compliance to the system. The compliance allows the front whegs to come into phase when an obstacle is encountered, so that both whegs can be used to lift the robot onto the obstacle. However, the connection is not durable. The spring unwinds easily after repeated use and must be replaced.

Mini-Whegs 2 uses a piece of Delrin® polymer for the flexible shaft. The Delrin® component is relatively long in order to add some torsional compliance. At the pivot point, two perpendicular slots are cut into the axle. The Delrin® bends about these slots, creating a sort of solid universal joint. However, the slot also creates a stress concentration, so after repeated use, the connection breaks.

Mini-Whegs 3 returned to a spring solution, this time with some plastic tubing added inside the spring to keep it from collapsing. While being somewhat more durable, many of the problems with Mini-Whegs 1 remain.

Thus, for Mini-Whegs 5, flexible materials were abandoned entirely. The required two degrees of motion are achieved through a pinned ball and cup mechanism (inspired by Althof, 2002). A ball on the end of the driven axle fits into a cup which forms the rotating hub to which the wheg is attached (Figure 4.2). The cup is held in place by a bearing in the steering upright. A slot is cut into the cup. A short pin through the center of the ball slides in this slot, providing the first degree of freedom. The cup can also rotate around the pin, providing the second perpendicular degree of freedom. When the pin pushes against the side of the slot, the cup rotates with the driven axle, so that the wheg can rotate as well. This simplified universal joint completely eliminates any torsional compliance, but is also durable and reliable.

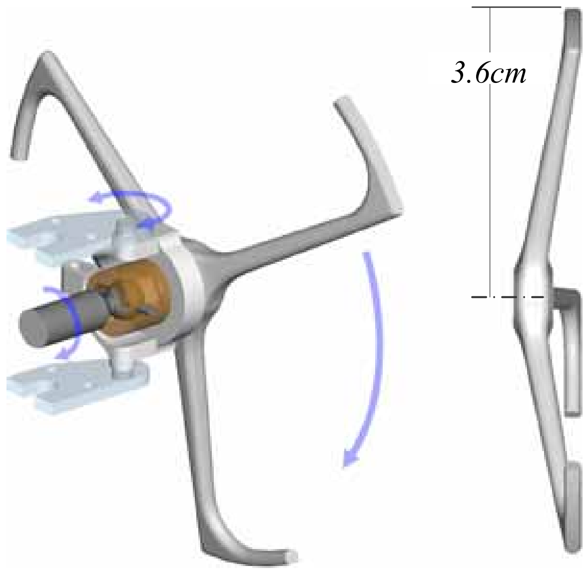


Figure 4.2 – Rendering of the ball and cup steering joint first used in Mini-Whegs 5.

Unlike a flexible spring, the mechanism has an exact center of rotation, so the uprights must be designed to rotate about the same axis. So, some careful design is required to ensure that all of the components line up correctly when assembled. In addition to placement of axes, the dimensions of the ball and cup must be chosen to allow the whegs to pivot as far as possible before the geometry collides. The cup should be as long as possible to ensure that the pin stays in contact with the slot, but it can not be so long that it collides with the axle. To increase the range of motion, the driven axle tapers to a much smaller diameter before the ball is reached. This allows the cup walls to pivot further around the ball before hitting. Some compromise is necessary to maintain a large enough diameter in the axle so that it does not break. The final dimensions used allow the cup to pivot ±30° without interference.

In Mini-Whegs 5, the balls on the end of the driven axle are machined into the steel shaft with a computer controlled lathe. Since the balls are machined into opposite ends of the same shaft, the exact length is somewhat difficult to control due to the lack of physical stops in the lathe used to cut the parts. Since the cups are easier to machine and replace, they are machined from brass, which will wear faster than the harder steel. The materials used lead to a very durable and reliable mechanism. However, the steel and brass also make the mechanism very heavy.

Because of the durability and reliability of the ball and cup mechanism, Mini-Whegs 3 was modified to use the same design. The driven axle was machined in two half-pieces to allow the length to be adjusted to fit the robot. Each half axle narrows down and fits into an aluminum sleeve, where it is held in place by set screws. In addition to allowing the length to be adjusted, the two half pieces also allow the offset to be adjusted so that an exact 60° offset can be achieved.

In order to reduce the weight of the steering mechanism, Mini-Whegs 7 does not use brass or steel parts. The driven axle consists of a hollow aluminum shaft which is threaded to accept two anodized aluminum ball studs, purchased from a radio control toy supplier. The ball studs must be drilled to accept a pin and turned down slightly to fit through bearings, but overall the modifications are much simpler than machining a ball into a solid shaft. The exact length required is also easy to achieve because the axle is a simple flat end hollow shaft.

The cup which mates with the ball on the end of the axle is machined from aluminum stock. Since the ball stud has been anodized, galling between the cup and the ball is not an issue. Unfortunately, because the ball stud was not specifically designed for this application, somewhat less travel of the cup (about ±25°) is possible. However, the different geometry also allows the cup to be slightly smaller, so it can fit into a smaller space. This reduces the overall width of the robot. The hollow shaft and aluminum components reduce the weight of the mechanism by over 7g (74%).

4.2 Leg and Foot Design

Like larger Whegs robots, Mini-Whegs employs several three-spoke appendages called whegs for locomotion. For the sake of simplicity and reduced size, the Mini-Whegs series of robots uses just four whegs, which results in an alternating diagonal gait. While the full size robots use six whegs to create an alternating tripod gait, Mini-Whegs is small enough and fast enough that an alternating diagonal gait is sufficiently stable. The wheg appendages have been redesigned several times to improve the mobility of the robot.

4.2.1 Early Mini-Whegs Leg Designs

The first Mini-Whegs (Mini-Whegs 1) robot uses whegs which are constructed very much like the whegs of the much larger Whegs I robot. Each wheg consists of a Delrin® polymer hub drilled to hold three short lengths of steel wire (Figure 4.4 (A)). The wire legs are held in place using set screws. A fourth set screw keeps the wheg from spinning about the driven axle. Overall, these whegs are heavy for their size, stiff, and require many steps to machine and assemble.

Later Mini-Whegs robots (Mini-Whegs 2, Mini-Whegs 3, and Mini-Whegs 4) used a wheg design similar in size and shape to the whegs used in Mini-Whegs 1, but machined entirely out a single piece of Delrin®. The all-Delrin® design results in whegs which are somewhat flexible, lighter by 2g per wheg, and require no assembly (Figure 4.4 (B)). Instead of a sets screw to stop rotation, a rectangular slot is milled into the wheg hub. The slot mates with matching flats on the driven axle to keep the whegs offset by 60°.

Although straight spokes are excellent for reaching onto large obstacles, the sharp tips of the legs easily catch in rough surfaces, such as carpet. The flexible legs then bend, and finally release, causing the robot to somersault, and making it difficult to control. In addition to catching on rough surfaces, the tiny contact patch of the tip of the leg offers almost no traction on hard, smooth surfaces.

4.2.2 A curved foot improves performance

The wheg design developed for Mini-Whegs 5 is similar to the previously used all-Delrin® design, but adds a short foot to the end of each leg spoke (Figure 4.4 (C)). The foot consists of an arc segment with a radius equal to the length of the leg spoke. The length of the foot, described by the length of the arc in degrees can vary between 0° and 120°, from bare leg spokes to a complete wheel. A shorter foot yields better climbing ability, but is harder to control. A foot length of 25° provides a good compromise between smooth operation and obstacle clearance capacity. When paired with its lateral neighbor, offset by 60°, the 25° arcs provide almost 50% of a complete wheel. Nominal body motion is decreased from 13.4% of the leg length to 4.6%. The foot is also short enough that it does not extend far past the front of the body when in contact with the ground, so climbing ability is hardly affected. The whegs with short feet are shown on the robot in Figure 4.3.

Figure 4.3 – Mini-Whegs 5. The front of the robot is on the right side of the photo.

The addition of the foot completely eliminates somersaults and removes a great deal of body motion, making the robot much easier to control. However, the exposed toe of the foot can still catch on tangled objects such as string, cable, or vegetation. Also, the heel of the foot where it attaches to the spoke is squared off. This extends the reach for climbing as long as possible, but it also creates a jarring impact every time the leg hits.

Traction on smooth hard surfaces is improved greatly by dipping the feet in Plasti Dip®, a rubbery plastic coating usually used for tool handle grips. Unfortunately, dirt and dust stick easily to the coating, making it less tacky and less effective at gripping the smooth surface. The coating also wears down quickly during repeated operation of the robot, so some secondary method for improving traction is desirable.

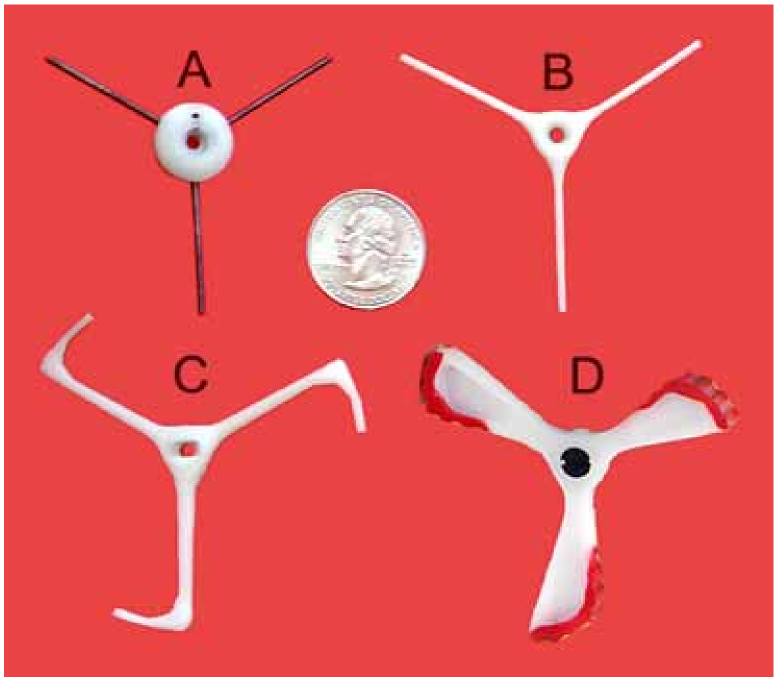


Figure 4.4 – Wheg appendage evolution of Mini-Whegs robots. A quarter is shown for scale.

4.2.3 Further wheg design development

In order to solve traction and tangling issues, and to further improve walking smoothness, the wheg shape for Mini-Whegs 7 was completely redesigned. It has since been adapted at a number of different sizes for three Mini-Whegs robots. Elements of the leg shape and construction have also been adapted for mid-size and full size Whegs robots as well.

The heel of the foot is designed to be parallel to the ground when it first makes contact. The radius of the foot arc then increases toward the full length (Figure 4.5). Thus, the impacts onto a sharp corner are eliminated. The contact patch of the foot is wider to add traction. Small ridges are also cut into the foot and back of the leg to add gripping surfaces. These ridged surfaces are then coated with Plasti Dip® to improve traction on hard, smooth surfaces.

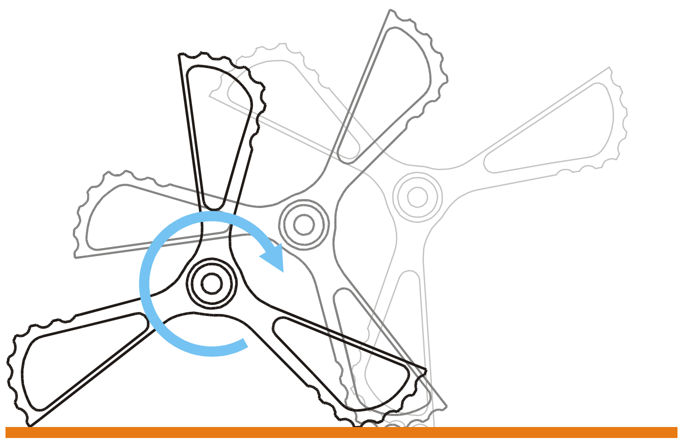


Figure 4.5 – A rounded heel smooths the transition between spoke impacts.

A thin web of material connects the toe of the foot back to the hub of the wheg, eliminating some of the tangling in foreign objects, especially while moving backwards. However, during machining of the first set of whegs of this improved design, it became apparent that the web was too thin and flexible by itself. It broke easily. In addition the stress concentrations at the roots of the ridges along the leg and foot caused part failures. These problems were remedied by adding some extra thickness to the foot and leg, while also adding another thin web of material filling in the space between the leg and toe-hub connection. Thus, there are no openings or extrusions in the final wheg design, so problems with tangling are virtually eliminated (Figure 4.4 (D)).

The final design uses significantly more material than earlier designs and the final Delrin® legs weighed 4.1g apiece, so some research into lighter materials was justified. Some prototype whegs were created using stereolithography (SLA). However, these legs, while weighing 3.3g were far too brittle for extended use and soon fractured near the hub during normal operation. Whegs formed from ABS plastic using fused deposition modeling (FDM) weighed 3.0g. Unfortunately, while lightweight, ABS does not have high tensile stress, and is stiff and somewhat brittle. Whegs milled from ABS sheet have very similar properties to those modeled using FDM. Milled Delrin® appears to be the best available solution. While Delrin® is a relatively dense polymer, it has the advantage of tensile strength 150% greater than ABS while retaining some flexibility, even with the stiff design resulting from the reinforcement webbing. The extra traction, smoother ride, and easier control resulting from the more complex wheg shape justify the extra weight.

4.3 Quantification of improved Mini-Whegs performance

After making the several design changes as described in this chapter, the new designs were tested to measure the improved performance and to provide a baseline for comparison to future robots.

4.3.1 Methods

Testing of Mini-Whegs 5 was primarily concerned with comparing the performance of whegs versus the performance of the same robot with wheels of the same diameter replacing the whegs. All experiments were recorded on digital video tape at 30 frames per second.

In order to determine the top speed of the robot, the carpeted floor was marked with tape at intervals of 91cm. The robot was then controlled to run at full speed across the tape strips while being video taped. After three trials, the wheg appendages were removed and replaced with wheels. The wheels were of a similar width as the wheg feet and had the same radius as the spoke length of the whegs. Three trials were also run with wheels.

Steering radius was also quantified in a similar manner. The robot was driven in a semi-circle across a ruler with the steering servo in its extreme position. Strips of tape were also placed on the floor at intervals of 15cm to assist in examining the video later. Several trials were run using whegs and wheels.

In addition to comparing whegs to wheels on flat surfaces and across obstacles, Mini-Whegs 5 was steered up an incline of varying angle using different wheg shapes, including the simple feet originally designed, and a larger version of the whegs designed for Mini-Whegs 7. Several angles and several trials were used for each shape.

4.3.2 Results

From the video recordings, it was relatively easy to determine in which frame the robot crossed each strip of tape. By counting frames between tape crossings, six sets of times for the 91cm distance were found for each case. From these times, the average top speed of the Mini-Whegs 5 using whegs was determined to be 10 body lengths per second. Using wheels on the same drive train results in an average speed of 15 body lengths per second, 50% faster.

The turning radius using whegs depends upon the orientation of the whegs at the beginning of the turn, but can be as tight as 2 body lengths or as large as 3 body lengths. The turning radius of the robot when using wheels is consistently 2.5 body lengths—equal to the average turning radius using whegs.

Mini-Whegs 5 was able to crawl over a 3.8 cm obstacle almost without fail when driven directly toward it (Figure 4.6). With wheels instead of whegs, the robot cannot climb across the obstacle at all.

Figure 4.6 – Composite of video frames showing Mini-Whegs 5 traversing two 3.8cm by 8.9cm obstacles while running at three body lengths per second.

After running several trials with Mini-Whegs 5 using the whegs with short arc feet, it was determined that the robot can climb on smooth surfaces up to 13° before sliding backwards, and up to 30° on a carpeted surface before flipping upside down. The extra traction from the improved, wider wheg design with small ridges allows the robot to climb smooth inclines up to 20°. Climbing on a carpeted surface is also improved somewhat to a maximum angle of 32.5° (Bittle and Cullen, 2004).

Chapter 5 – First Attempt at Independent Running and Jumping

After successful demonstration of the jumping concept in Mini-Whegs 4J, and after developing other robust components in Mini-Whegs 5, design began on a robot to combine elements of the jumping prototype and the reliable platform to create a fully controllable robot with independent running and jumping modes of locomotion.

5.1 Motor Selection

In order to separate jumping from running, another actuator must be added to the robot. While several methods were considered, including the addition of a solenoid activated clutch between the drive motor and a secondary transmission, the addition of a completely new motor for jumping was determined to be the most viable solution. The torque requirements for extending the spring on Mini-Whegs 4J were measured experimentally using suspended weights to cancel out the torque created by the spring as part of senior project by Dave Johnson (Johnson 2002).

From the torque requirements, it was then possible to select a larger motor and transmission. The motor and transmission combination must create the required torque without drawing more than about 1A, the maximum current the batteries can provide.

The Maxon transmission with the highest allowable intermittent torque, while staying at a size suitable for Mini-Whegs, is a 13mm, 1119:1 planetary metal gear transmission. This is a much smaller reduction than the 18,545:1 reduction from the two transmission combination in Mini-Whegs 4J. The larger load on the motor necessitated the selection of a larger 2.5W motor instead of the 1.2W motor previously used. However, the reduced gear reduction has benefits as well—the wind time would be about 10 times faster, and eliminating a second transmission also reduces friction, making the robot more energy efficient.

5.2 Design

Most of the components for Mini-Whegs 6J are similar to the components from Mini-Whegs 5 and Mini-Whegs 4J. However, placement and dimensions of the parts had to be modified in order to fit all the elements into the new design. The frame needs to be long enough for the front wheg axle, rack and pinion steering, steering servo, batteries, drive motor, jumping mechanism motor, jumping mechanism drive axle, rear wheg axle, and rear jumping mechanism axle, with adequate clearance for chain sprockets and bearings (Figure 5.1).

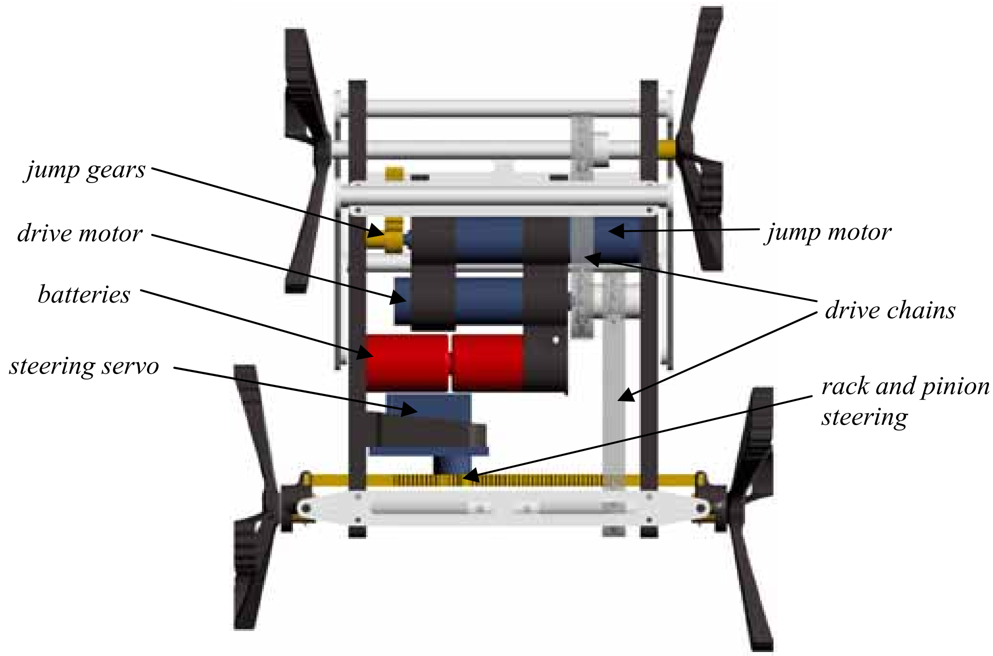


Figure 5.1 – Top view of Mini-Whegs 6J with labels indicating components that affect the size of the chassis.

5.2.1 Chain Sprocket Selection and Spacing

All Mini-Whegs robot use sprocket and chain drives to connect the central drive motor to the front and rear axles. In most previous Mini-Whegs robots, the spacing has allowed the chain to hang too loosely, necessitating chain tensioners or causing problems with snagging.

To help alleviate chain snagging, sprocket sizes were chosen to minimize chain contact with other components. The sprocket on the front axle must be small to allow the steering rack to come as close as possible to the front axle, resulting in the greatest steering upright rotation for a given servo travel. The sprocket must also be big enough to keep the chain from rubbing against the rack. For these reasons, ten tooth sprockets were selected for the drive connection between the front axle and motor. In the rear half of the robot, the chain must travel around the jumping mechanism motor. Fourteen tooth sprockets were the smallest sprockets which would allow the chain to move unhindered by the jump motor housing.

To choose the spacing between sprockets, a series of holes were drilled in two sheets of Delrin® plastic. Each set of holes was slightly further apart than the previous set. Axles with sprockets were then mounted in the holes. A 34 link chain was then wrapped around the axles. The slack in the chain was measured using calipers. The experiment was repeated for three different hole spacings for both 10 and 14 tooth sprockets. The actual length of the chain was then estimated from the geometry of the slack chain and compared to the calculated length of the chain (Figure 5.2). The complete chain length calculation can be found in Appendix B.1 .

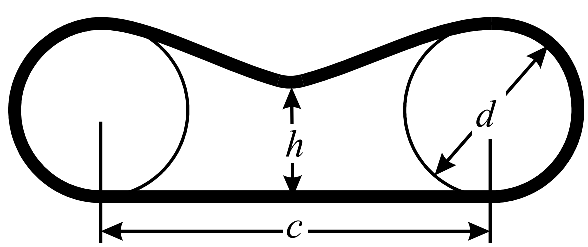


Figure 5.2 – The stretched length of the chain can be approximated if the pitch diameter (d) of the chain sprockets, the center distance (c) between the sprockets, and the height (h) at the center of the chain are known.

From the six trials, the actual length of the chain in its stretched configuration was found to be about 0.6% to 1.2% longer than the calculated length of the chain. Since the chain should be taut, but not stretched, the dimensions used in the Mini-Whegs 6J design were based on an extra length of 0.3%.

5.2.2 Jump Gear Selection

The jumping mechanism in Mini-Whegs 6J is retracted and released using a slip-gear arrangement like Mini-Whegs 4J. The pinion of the slip-gear is a 32 diametrical pitch spur gear with several teeth removed. It drives a second complete gear to retract the mechanism. When the section without teeth is reached, the driven gear slips, releasing the jumping mechanism (Figure 3.3).

Mini-Whegs 4J uses a pair of aluminum 14 tooth gears. However, the center distance between the 14 tooth gears would cause interference between components in Mini-Whegs 6J, so a different set of gears is required. Also, since the new motor has a smaller transmission than Mini-Whegs 4J, an extra gear reduction is desirable. First, brass was selected for the material of the gears to ensure more even wear than with the aluminum gears. The smallest brass 32 pitch gear available from McMaster-Carr (12 teeth) was selected for the slip gear. Then, the smallest available gear (18 teeth) which would still leave a center distance long enough to allow for both the new motor and jump axle bearings was selected, for a total gear reduction 3:2.

The number of teeth to remove from the 12 tooth slip gear was calculated using the contact ratio for the gears. For the 14 tooth gears, 3 teeth remained for retracting the mechanism. The total teeth in contact for the duration of the retraction is twice the contact ratio (for the outside teeth), plus the sum of the remaining inside teeth. For the 14 to 14 tooth gear pair, the contact ratio is 1.463 (Appendix B.2), so the number of teeth in contact is $2\times1.463 + 1 = 3.926$. Thus, the total rotation of the driven gear is $3.926/14 \times 360° = 100.9°$. For the 12 to 18 tooth gear pair, the contact ratio is 1.475, so the total number of teeth in contact if 4 teeth are left intact is $2\times1.475 + 2 = 4.950$. This gives a rotation of $4.950/18 \times 360° = 99.0°$. The 1.9% difference in rotation should be insignificant in retracting the mechanism.

5.2.3 Other Physical Modifications

The chassis of the robot was lengthened and widened to make room for all the additional components. All the components of the robot were modeled in Pro/ENGINEER and assembled in the CAD program to ensure that everything fit well. Figure 5.3 shows the assembly of all the computer designed components. Thicker material was used for the Delrin® side rails of the robot to add strength at the increased length. Jumping mechanism legs were lengthened to fit just behind the steering rack of the robot. The final chassis is 12.4cm long by 8.4cm wide.

Figure 5.3 – Rendering of the complete Pro/ENGINEER model of Mini-Whegs 6J.

5.2.4 Control System

A dual speed controller system was selected to operate the running and jumping mechanisms. A miniature 4 channel radio receiver which incorporates a unidirectional speed controller on one of the outputs was ordered from Sky Hooks & Rigging, a Canadian model aircraft supplier. The speed controlled channel would be used to control the jumping motor. A miniature switch activated by the position of the slip-gear pinion was considered to aid the operator in controlling the jumping mechanism, but was ultimately left out for simplicity. Instead, the operator must watch the robot to see when it is fully retracted, and the stop the jumping motor. When jumping is desired, the operator simply moves the throttle on again to complete the rotation of the pinion. A second bi-directional speed controller was selected to control the drive motor for forward or reverse operation.

5.3 Spring Selection

After the parts for the robot were machined and assembled using a miniature CNC (Computer Numerical Control) mill and some hand-machining, spring selection was attempted using a combination of calculations and experiments. The maximum allowed force in the spring was determined using the maximum torque figures from the Maxon specifications for the transmission. Then available springs from McMaster-Carr were identified and ordered to meet the maximum specifications and greatest possible preload. The springs were then mounted on the robot and tested individually for the best results.

5.4 Results

Unfortunately, the robot did not perform as well as Mini-Whegs 4J. The stiffest springs that the jumping motor could wind were insufficiently stiff to cause the robot to jump. This was primarily caused by the increased weight of the robot and the long lever arms of the spring attachment and jumping leg lengths. While Mini-Whegs 4J weighed approximately 200g, Mini-Whegs 6J weighs almost 300g. The excess weight also made the robot very slow during normal walking. Not only was Mini-Whegs 6J large and heavy, it was also expensive to construct due to the use of multiple Maxon motors, titanium jumping legs, and miniature custom radio control components. The next Chapter discusses a completely new Mini-Whegs built to reduce the weight, size, and cost.

The problems with Mini-Whegs 6J led to a clear problem statement for the development of a new robot. Most importantly, the robot needed to be lighter and smaller. Additionally, there were goals to design a robot which would be closer to a complete product. Thus, other goals included an enclosed, more weather resistant body, more commonly available parts, and a component and materials cost of less than $250.

Chapter 6 – Weight, Size, and Cost Reduction

The initial combination of steering and controlled jumping in Mini-Whegs 6J led to a robot that was too heavy. The addition of a second motor and other jumping components made Mini-Whegs 6J weigh 294g, almost twice as much as Mini-Whegs 5. The extra weight meant that the drive motor was barely able to move the robot. Also, the jumping motor was not strong enough to wind a spring stiff enough to make the robot jump. Since no more powerful motors were available in a comparable size, Mini-Whegs 6J research was set aside until a lighter platform could be developed. This chapter covers the design of Mini-Whegs 7, including the selection of components and materials, the manufacture and assembly of the robot, testing of the completed design, and results.

6.1 Design Goals and Specifications

The lightest successful Mini-Whegs robot built before Mini-Whegs 7 weighed 147g. By reducing the size of the robot, and using lighter materials and components, this weight could be reduced significantly. The combined weight of the jumping motor and four-bar linkage on Mini-Whegs 4J is about 80g, so in order to serve as a viable platform for the addition of a jumping mechanism, Mini-Whegs 7 had to be able to carry a payload of at least that much. This led to a target weight of 100g for the new robot. By achiving this target weight, a combined running and jumping robot would be expected to weigh less than Mini-Whegs 4J.

In addition to the target weight, the robot was to be smaller than Mini-Whegs 3 while still being able to surmount obstacles up to 3.8cm high and run at over 3 body lengths per second. The open frame design of previous Mini-Whegs robots makes them unsuitable for extended outdoor use, so all the components of Mini-Whegs 7 were to be enclosed within a clamshell chassis. The total cost of the parts purchased and the materials used in machining should not exceed $250, excluding labor.

In order to achieve the design goals, the following specifications for components were set. The drive train should use a single plastic chain with smaller sprockets to leave more room in the robot for other components. Axles should be the same diameter as in previous Mini-Whegs robots, but should be hollow to reduce weight. The drive motor should weigh less than 20g, but should provide high torque and speed to propel the robot at over 3 body lengths per second. The steering components, including the front axle, should use lighter materials than the brass and steel used in Mini-Whegs 5 and 6J. Ball studs of the same size as the balls machined on the axle of Mini-Whegs 5 were to be purchased to be screwed into the front axle. This would allow the remainder of the axle to be hollow. In order to achieve the cost goal, a cheaper radio receiver, preferably with standard connectors to ease assembly, was required.

6.2 Component Selection

Previous Mini-Whegs robots all used 13mm Maxon motors to drive the Whegs. Maxon motors are well suited for Mini-Whegs since they provide a large amount of torque at a high speeds. However, the metal gears make them heavy. The motor and transmission combined in Mini-Whegs 5 weighs 32g. Also, Maxon motors draw current up to 2A, which means that battery selection for powering the motors is limited. To try to overcome some of these obstacles, some research into alternative motors was necessary.

William Lewinger, the electrical engineer assisting with the project, suggested that it would be possible to modify a hobby micro-servo to achieve continuous rotation at the output shaft, instead of the normal ±45º rotation. By replacing the potentiometer in the servo circuit with a pair of constant resistors, the circuitry would create a speed controller instead of a position controller. Thus, manufacturer specifications for a number of different micro-servos were compared to find a suitable candidate. The MPI servo model MX-50HP, which weighs 9.1g, was selected for its high power to weight ratio, its small size, and it's relatively high speed. It was estimated that the servo would be able to provide similar speeds to the Maxon motor at about half the torque. Since previous Mini-Whegs robots did not lack torque, the lower torque figure was expected to be a valid tradeoff for lower mass and cost. Appendix C.2 details the comparison between the Maxon motor and MPI servo.

Figure 6.1 – Photo of the interior of Mini-Whegs 7, showing the single drive chain, wheg axles, servos for drive and steering, and radio receiver.

All Mini-Whegs robots, with the exception of Mini-Whegs 2 used a pair of stainless steel 0.1475 pitch chains and aluminum sprockets to connect the drive shaft to the axles. To reduce weight and ease assembly, a 0.1227 pitch acetal chain with acetal resin sprockets was selected for the new design. To save further room and weight, only a single chain, wrapped around the drive shaft sprocket in a U shape, was employed.

Previous designs used a custom radio control receiver designed for ultra-lightweight model aircraft. While very small and light, the receiver was expensive, hard to get, and had unreliable electrical connectors. To reduce costs and improve the availability and reliability, a different receiver was required. The selection for micro radio receivers is somewhat limited, especially since the receiver had to be compatible with existing transmitters in the laboratory. Finally, the Hitec “Feather” four-channel receiver, which offers standard size connectors, was selected. It is 3.3cm by 1.9cm by 1.0cm in size and weighs 7.4g as compared to 2.4cm by 1.9cm by 0.cm and 3.3g for the Sky Hooks and Rigging receiver used in Mini-Whegs 5. The receiver and servos used to control Mini-Whegs 7 are shown inside the robot in Figure 6.1.

Standard radio control parts, such as the servos and receiver being used, require between 4.8 and 6 Volts to run properly. The high torque, high speed motors driven by the batteries also require relative high current, on the order of 100mA or more. Most readily available small batteries cannot meet both the voltage and current delivery requirements. There are a few cells, primarily designed for camera applications, that do meet the needs of Mini-Whegs robots. These include the 3 Volt CR2 cells used on previous Mini-Whegs designs, which weigh 11g each and are 1.6cm in diameter by 2.6cm long. However, since 2 cells are needed to reach 6 Volts, a significant portion of the size and weight of the robot is taken up by those batteries. Thus, the smaller, 6 Volt 2CR-1/3N cell was selected for testing. It weighs only 9g and measures 1.3cm in diameter by 2.5cm long. Brief unloaded tests with two servos and a receiver indicated that the battery was capable of powering the robot. Later tests with the completed Mini-Whegs 7 showed that, while the robot was able to move with the smaller battery, the higher current delivery capacity of the CR2 cells provided greater mobility.

6.3 Part Design and Material Selection

The body of Mini-Whegs 7 was designed to reduce weight and to make the robot easier to assemble by reducing the number of fasteners. Previous robots used a pair of

Delrin® rails connected by aluminum cross-members, held together with 16 #0-80 screws, to hold all the components in place. The steering components, radio receiver, and drive motor were held in place with even more screws. The new design consists of upper and lower Delrin® shells which hold two side inserts in place. Delrin® was once again chosen for its good strength and machineability. In this case, all the chassis components were hollowed out significantly to reduce weight. The two halves are held together by 4 nylon #2-56 screws. Components are trapped vertically beneath the shells, and held in place horizontally by short walls, so no extra fasteners are required (Figure 6.2).

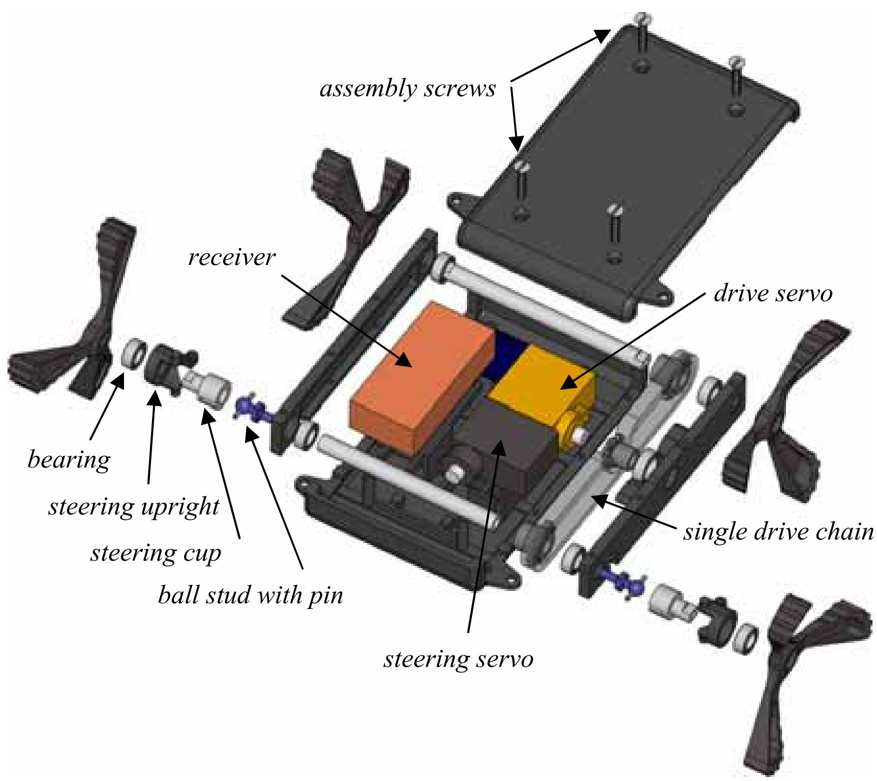


Figure 6.2 – Exploded view of showing the assembly of Mini-Whegs 7 components.

The steering mechanism design is a modification of the design used for Mini-Whegs 5, described in detail in Chapter 4. The front steering axle on previous robots was machined from steel to increase its life compared to the other steering components. However, similarly sized ball studs are readily available as steering linkage parts for radio control cars. By using the anodized aluminum ball studs instead of machining balls on the ends of the axles, steel was no longer required for the new design. Thus, both front and rear axles are hollow aluminum shafts. The ball studs are screwed into the hollow shafts and held in place with Loctite®. In previous robots, the steering joint cup was machined from brass for its smooth wear characteristics. Brass is 3 times more dense than aluminum, however. Since the steering joint ball is anodized, there is little threat of galling between the ball and the cup, so the cup was also machined from aluminum. If wear turns out to be minimal, the cup could be machined out of plastic, about half as dense as aluminum, in future robots to reduce weight even further. The rack and pinion which control the steering were produced from modified 48 pitch nylon gears. Once again, plastic was selected over brass to reduce weight.

Choosing the dimensions for the drive chain geometry was complicated. Choosing the distance between the axles based on only the pitch and number of links leads to a design in which the chain is too tight to move smoothly. Previous attempts to quantify the amount of slack necessary to allow smooth operation are not well suited for a complicated chain path because the discrete chain links do not follow the path exactly. Also, the previous tests only involved the original stainless steel chain, not the plastic chain to be used in the new robot. Instead of quantifying the slack on a per link basis, an iterative trial and error method was used. For each iteration, the distance between the axles was reduced by 0.13mm. The side inserts were then milled for that length. The bearings, axles with sprockets, and the chain were inserted into the corresponding holes. By spinning the axle using ones fingers, a qualitative estimate of the smoothness of rotation was made. After three iterations, the chain movement was deemed taut enough to avoid snagging on the side rails while loose enough to eliminate most of the friction. The final geometry is illustrated in Figure 6.3.

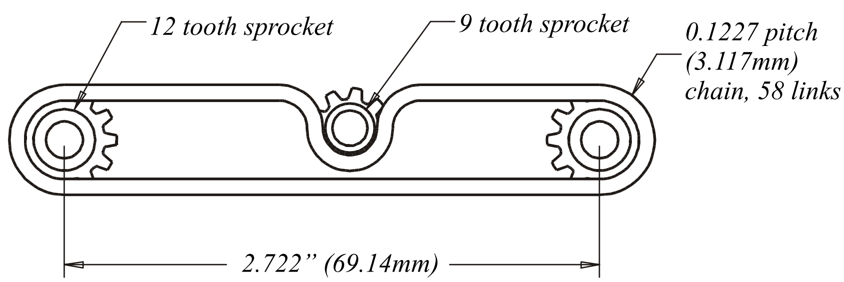


Figure 6.3 – Chain geometry for Mini-Whegs 7.

6.4 Manufacture and Assembly

Once all the components were selected, parts were designed, and materials were selected, it was possible to manufacture the robot. Some of the steps in creating the robot involved modifying existing parts, while other components were machined from material stock.

For the steering servo and drive servo to fit into the chassis, the cases of the servos had to be modified slightly. As purchased, the cases include mounting tabs which needed to be removed. This did not affect the performance of the servos; it simply reduced their size. The output shaft of the drive servo was machined into a cross shape using a small computer controlled (CNC) mill. The sprocket which mates with the servo was similarly modified so that the two parts would fit together.

The steps for modifying the drive servo for continuous rotation were complex. First, the case was removed and the reduction gears were pulled off of the potentiometer shaft. Next, the physical stops inside the potentiometer and on the reduction gears were removed. Finally, the potentiometer leads were disconnected from the servo circuit and replaced by a pair of equal resistors.

The steering joint balls were drilled to accept a 1.14mm diameter piece of music wire. This wire was fixed in place with Loctite®, and acts as the pin for the steering joint. The hexagonal base of each of the ball studs was also turned down to the same diameter as the 4.8mm diameter axle. The steering rack was cut to length from the purchased length of 48 pitch nylon rack. Then, all of the teeth except for those near the center were removed. The ends were then drilled and tapped to accept a #0-80 screw.

The models for the chassis base, top, and inserts, steering uprights, and whegs were combined into assembly files in Pro/ENGINEER. These assemblies were exported as STL files and then machined from Delrin® sheets using a small CNC mill. After milling, the parts were removed from the assembly frames and sanded to remove any remaining sprues. The last step in constructing the chassis was to drill and tap the four assembly posts of the chassis base.

Finally, the aluminum steering cups and the axles were machined by hand from aluminum rods using a lathe for preliminary shaping, and then a mill to add flats and slots.

After all the parts were machined, Mini-Whegs 7 was assembled. A hole was drilled in the chassis base to allow the receiver antenna to pass through (Figure 6.4). The antenna was then coiled around the base of the robot and held in place with two strips of double-sided tape. The electrical engineer helping with the project soldered the electrical components for the battery holder and helped to route the wires from the servo and receiver. Sprockets were press-fit onto the axles, and bearings were press-fit into the cavities in the chassis inserts. Finally, the axles were placed inside the bearings, connecting the two inserts. The servos and receiver were held in place and then the entire subassembly was snapped onto the pins of the chassis base. Slight trimming of the assembly screws was necessary to allow the chassis top to close completely. The feet of the whegs were coated with Plasti Dip® rubber coating to improve traction, and were then attached to the axles and steering joint cups with nylon screws.

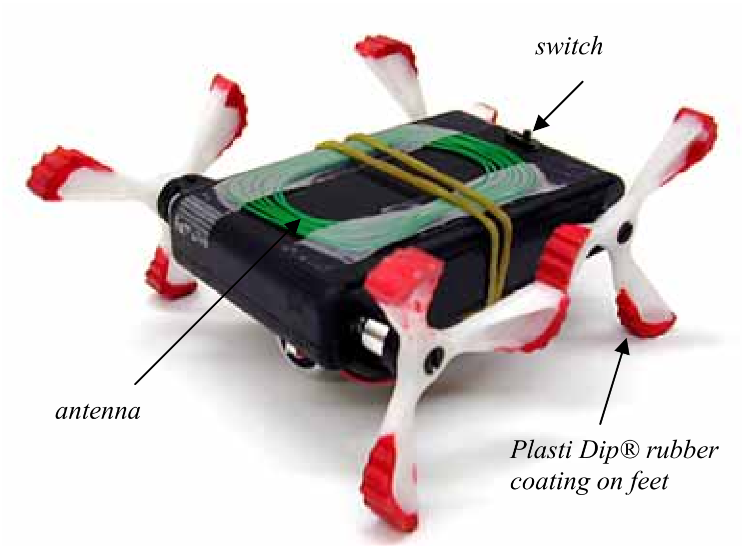


Figure 6.4 – Bottom of the fully assembled Mini-Whegs 7 showing the rubber coating and coiled antenna. The rubber band holds the larger batteries in place.

6.5 Testing

The first time Mini-Whegs 7 was turned on, whining noises made it evident that friction was a problem. However, the servo made almost as much noise inside the robot as outside, so a second servo was modified for continuous rotation. The internal gears of the new servo were also greased to improve smooth operation. Additionally, the axles were turned down slightly near the assemble posts to prevent rubbing.

After these modifications were made, the robot was tested with a power supply with an internal ammeter. The current draw with the first servo in the robot was about 250mA. With the modified servo and other improvements, the current draw dropped more than 30%. The current draw was the same regardless of whether the servo was inside the drive train or completely removed from the robot. Thus, no further attempts were made to reduce friction in the drive train. See Appendix C.3 for the data from these tests.

6.5.1 Quantitative Tests

The testing with the external power source showed that the servo was capable of higher performance than was seen with the single 6 Volt cell. Thus, a makeshift rig was assembled to attach a pair of 3 Volt CR2 cells to the top of the robot. Top speed tests were then made to compare the performance with the different power sources.

Top speed tests for previous robots were run on the laboratory carpet past tape markings at one foot intervals. The good traction of the rubber coating on the feet probably enabled it to go faster on a hard linoleum surface, but this was not quantified, since previous Mini-Whegs were all tested on the carpet. The runs were video recorded, and then analyzed frame by frame to determine the speed of the robot. Results showed that Mini-Whegs 7 was about 40% faster with the CR2 cells than with the single 6 Volt cell. The complete results are listed in Appendix C.4 . The 20% weight increase for such a large increase in performance seemed to justify using the larger batteries, so subsequent mobility tests were carried out with the large batteries only.

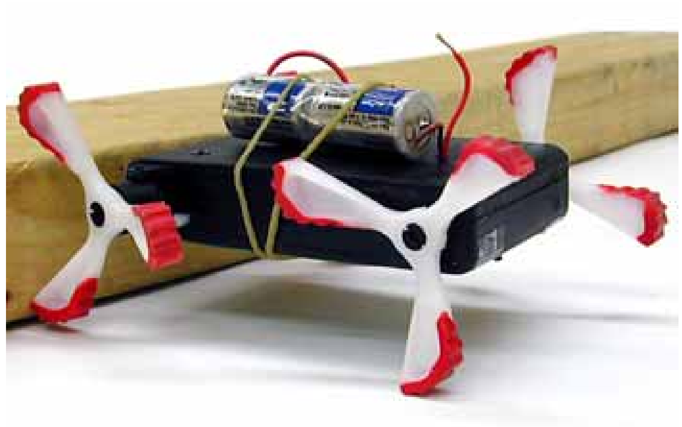


Figure 6.5 – Photo depicting the relative height of a 3.8 cm obstacle to the size of the robot.

Mini-Whegs 7 was also controlled to run over obstacles of various heights. The largest obstacle successfully overcome, without high-centering and toppling of the robot, measured 3.8cm (Figure 6.5, Figure 6.6). This height is 25% higher than the length of any leg at its longest point. If some mechanism, such as a flexible tail, existed to prevent toppling, larger obstacles could almost certainly be surmounted.

Figure 6.6 – The robot is able to surmount the 3.8 cm obstacle.

A brief examination of testing videos indicated that the turning radius of the robot was about three to four body lengths. This is a somewhat larger turning radius than previous Mini-Whegs designs. However, the geometry of the steering joint ball in previous robots was optimized for a large angle. With the current robot, such an optimization was not possible without considerably more modification of the purchased ball studs.

The robot was also tested on a carpeted incline at various angles. When the speed of the robot was sufficiently reduced, it was able to climb inclines up to 25º. At higher speeds, the front whegs had a tendency to pop off the surface of the incline and cause the robot to topple backwards.

Payload capacity was also measured to examine whether a servo-powered robot would be able to support the extra components of a jumping mechanism. Several brass masses, ranging from 50g to 200g, were attached to the top of Mini-Whegs 7 with double sided tape, which was then operated. The robot was able to move at over 3 body lengths per second while carrying a payload up to 100g. With larger payloads, the robot was still able to move, albeit at less than 3 body lengths per second. A payload of 200g slowed the robot to 2 body lengths per second.

6.6 Mini-Whegs 8

As a senior project, Andrew Schifle and Elizabeth Steva created a second lightweight robot, Mini-Whegs 8, which has a slightly larger chassis to accommodate the CR2 cells used in most of the testing of Mini-Whegs 7 (Schifle and Steva, 2004) (Figure

1.4). Mini-Whegs 8, at 9.5cm by 6.7cm by 1.8cm, is smaller than Mini-Whegs 5 (9.1cm by 6.9cm by 2.0cm and 165g), but weighs the same amount as Mini-Whegs 7 (108g). The increase in size with no increase in weight was accomplished by using ABS, a less dense plastic than Delrin®, for the clamshell chassis. The larger size, slightly longer wheg appendages, and lowered center of gravity (since the batteries are not on top of the robot) allow Mini-Whegs 8 to climb 3.8cm obstacles more reliably than Mini-Whegs 7.

6.7 Discussion

Several objectives were met with the design of Mini-Whegs 7. The weight of the robot with its single battery beat the target weight by over 10%, but was over the target by 8% with the two battery configuration. While not as fast as previous Mini-Whegs robots, the robot was still able to move at almost four body lengths per second. Obstacle climbing ability was on par with earlier designs. The cost, at just under $180 (see Appendix C.1), of the current robot was much less than previous Mini-Whegs robots.

With a payload of 50g, Mini-Whegs 7 was almost as fast as with no extra mass at all. Extra mass of up to 100g—the robot's own mass—caused the robot to slow a little more. However, the top speed was still over three body lengths per second. Thus, addition of a jumping mechanism would still allow the robot to beat the target top speed.

The next Chapter discusses how the design changes made in Mini-Whegs 7 and 8 were combined with some of the successful features of Mini-Whegs 4J and 6J to finally create a fully controllable jumping robot.

Chapter 7 – A Fully Controllable Jumping Robot

Development of Mini-Whegs 7 and 8 successfully reduced the weight of the Mini-Whegs platform, making it possible to add extra payload, such as a jumping mechanism, without significantly reducing the mobility of the robot. Elements of the designs of Mini-Whegs 7 and 8 were combined with the four-bar mechanism design and spring-winding motor from Mini-Whegs 6J to create the fully controllable running and jumping Mini-Whegs 9J.

7.1 Design Goals and Specifications

As discussed in Chapter 6, payload testing on Mini-Whegs 7 showed that the servo used as a drive motor was easily capable of powering a robot weighing 200g. Since Mini-Whegs 4J weighs 200g with no control system and only one motor, it was unlikely that a completely controllable jumping Mini-Whegs robot could be built weighing much less than Mini-Whegs 4J. Thus, a target weight of 200g was set for Mini-

Whegs 9J. Not only was Mini-Whegs 6J heavy, it was also quite large. While designing Mini-Whegs 9J, a significant effort was made to pack the components closely, keeping the chassis the same width as Mini-Whegs 4J, 7.6cm, while keeping the distance between the front and rear wheg axle under 8cm.

Achieving the target weight and size requires some weight reduction in the jumping mechanism while retaining the weight reduction techniques used for the rest of the components in Mini-Whegs 7 and 8. The new robot should use the same drive servo, chain, and sprockets as those used in Mini-Whegs 7 and 8. If lighter or smaller steering servo or radio control components are readily available, they should be incorporated into the new design. All axles and jumping mechanism cross braces should be hollow. The jumping mechanism motor should weigh no more than the one used in Mini-Whegs 6J, and the four-bar linkage should use aluminum instead of titanium to reduce weight.

In addition to size and weight goals, performance requirements were also set. The length of the whegs combined with the low weight of the whole robot should result in a top speed of over 3 body lengths per second. The spring selected for the jumping mechanism should allow the robot to jump at least 15cm, the height of a standard stair.

7.2 Component Selection

In order to reduce size and weight, several components even smaller than those used in Mini-Whegs 7 were used. A Cirrus 4.4g servo was chosen to turn the pinion for steering, while a 3.5g Cirrus Micro-Joule radio receiver and 2g Cirrus Micro-Joule S5A2 speed controller were selected to control the jumping mechanism motor. As in Mini-

Whegs 7, an MPI MX50-HP servo was modified for continuous rotation to act as a drive motor for the whegs. The electronics of the servo act as a speed controller, so no additional speed controller is required for running.

Other components, such as rack and pinion for steering, and the ball studs for the simplified universal joints in the front wheg axle were the same as those used in Mini-Whegs 7. Aluminum was used instead of titanium for the jumping legs, and the aluminum braces for the jumping mechanism were hollowed to reduce weight even further.

7.3 Design

As with previous Mini-Whegs robots, all the parts were modeled in Pro/ENGINEER before being manufactured or assembled. Using the volume calculating capabilities of the CAD program, it was possible to monitor the mass of each component. In addition to providing an estimate for the final mass of the actual robot, the mass calculations showed which components required the most weight reduction to achieve the target total mass.

7.3.1 Chassis and component layout

The chassis of Mini-Whegs 9J is similar to that of Mini-Whegs 7 and 8. A pair of hollowed ABS side rails support bearings for the drive and jump axles. The side rails fit into a bottom shell, also made from ABS, via several small posts. The bottom shell contains several short walls and shelves to support the internal components, such as the motor and servos (Figure 7.1). A second shell fits over the top of the first and attaches with six #2-56 screws.

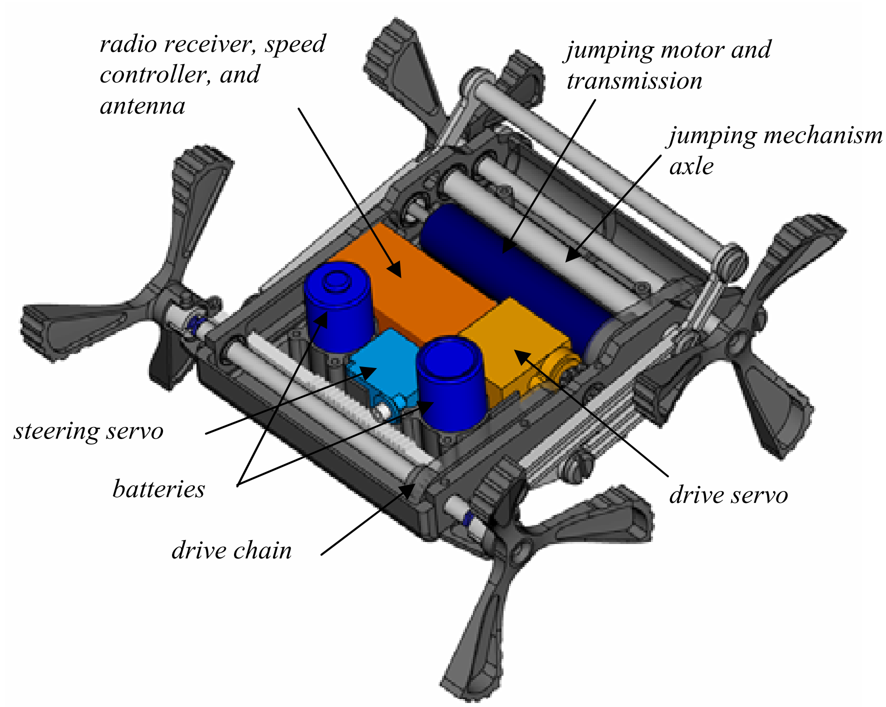


Figure 7.1 – Rendering of the internal components of Mini-Whegs 9J.

The spring of the jumping mechanism is external to the body, so the ground clearance is reduced when the robot is upside down. By placing the batteries for the robot vertically inside the body and protruding through the top, some of the lost space at the top of the robot was utilized. Placing the batteries vertically also allowed the length of the robot to be reduced to achieve the target length, and allows the batteries to be removed more easily when they need to be changed.

Inside the robot, the steering servo fits between the two batteries. The spring fits between the batteries on top of the robot, and attaches to a short aluminum protrusion in front of the battery housing (Figure 7.2). The batteries help to brace against the force of the spring. A small battery lid fits over the top of the batteries on the outside of the robot. Thus, the batteries can be changed by opening just the lid, without removing the spring or upper body shell. The lid is held in place by two #2-56 screws. It also contains a small switch to turn on the robot.

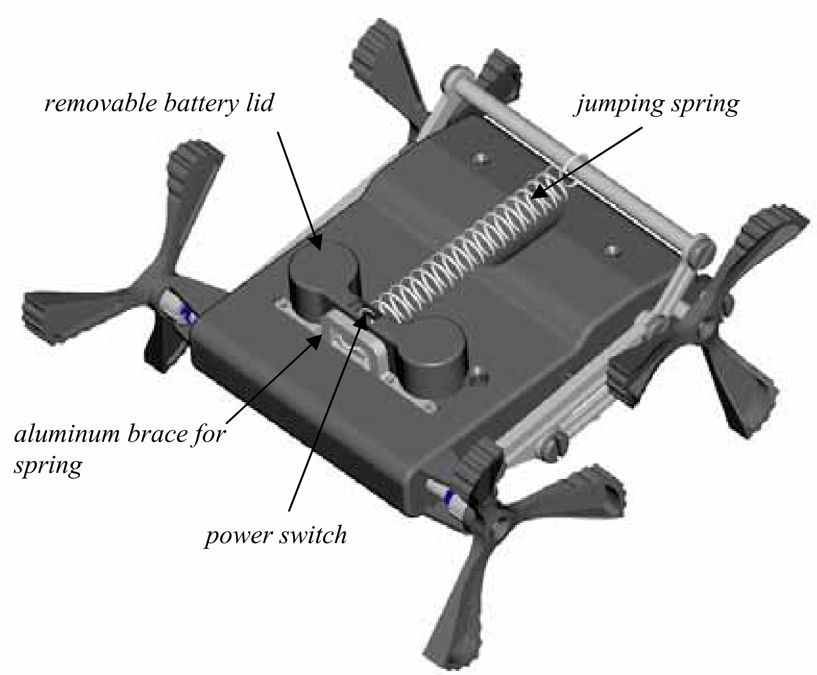


Figure 7.2 – Rendering of the complete robot. The jumping spring attaches to a brace in front of the batteries and fits underneath the removable battery lid.

7.3.2 Jumping mechanism modifications

In addition to reducing the weight of the components which appear in other Mini-Whegs robots, some design modifications were made to reduce the weight and cost of the jumping mechanism as well. The four bar mechanisms in Mini-Whegs 4J and Mini-Whegs 6J consist of titanium links attached to solid aluminum shafts with steel screws and washers, and brass bushings to reduce friction at the joints. While titanium is stronger than aluminum on a per mass basis, it is more expensive and denser. Since the links cannot conveniently be made any smaller than they already are on Mini-Whegs 4J, using aluminum would actually reduce the total weight of the links by 7g. In order to add needed stiffness, a single or double rib was added to the links to create a T or C shaped cross section. The resulting links are light (8g in total), easy to machine, and much less expensive than those made of titanium. An additional 5g were removed by using hollow aluminum shafts for cross braces with larger 8-32 nylon screws. The large diameter of the assembly screw allows the shafts to be thin-walled (3.0mm internal diameter in a 4.8mm shaft), while the large heads eliminate the need for washers to keep the screws from pulling through the holes in the links. Thin Teflon washers are used to reduce friction between the screws and the links. The complete assembly can be seen in Figure 7.3.

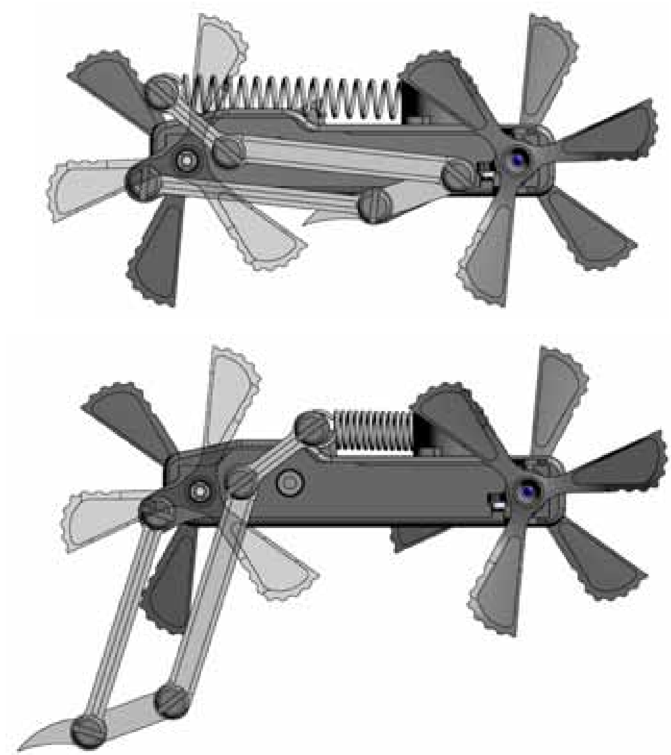


Figure 7.3 – Side view renderings showing the jumping mechanism of Mini-Whegs 9J retracted (top) and released (bottom).

The motor and transmission combination used in Mini-Whegs 6J was reused in Mini-Whegs 9J. Space between the transmission output shaft and the jumping axle remains the same, so the same size 12 tooth pinion and 18 tooth gear were used. However, to reduce weight by 5g, aluminum gears were selected instead of brass. The 18 tooth gear only rotates through about 100°, so about half of the teeth on the unused side of the gear were removed to reduce weight and improve clearance between the gear and the rear wheg axle.

7.3.3 Spring selection

After designing and assembling the new jumping mechanism, it was desirable to choose the spring would be able to store the maximum amount of energy possible when the mechanism was fully wound. Ideally, this spring would require the same amount of force to extend at any length. As discussed in Chapter 3, such a spring does not exist, so a soft spring with a significant amount of preload is desirable. For the same maximum applicable force, the softer spring will store more energy for a given displacement up to that force. However, there are also space considerations, so the spring cannot be stretched very far to build up preload. The dimensions of Mini-Whegs 9J limit the free spring length to a maximum of about 4.4cm. The spring must also be strong enough to avoid plastic deformation at the maximum load, so there is a lower limit of about 2.5cm in length and 0.8cm in diameter for readily available springs.

Two springs were selected from a random assortment which fit the size requirements. The first spring allowed the robot to jump into the air, but the second spring was too stiff for the motor to wind. Since the springs were from an assortment, no stiffness data were available. To remedy this situation, several weights of known mass were successively hung from the spring and the displacement was measured. The data points collected were used to plot the stiffness of the springs (Figure 7.4). From this information, several alternative springs were selected which fit the dimensional criteria and whose stiffness fit in between the stiffness of the two original springs. These new springs were then tested in the robot, and the one which resulted in the highest jump was selected for the final robot.

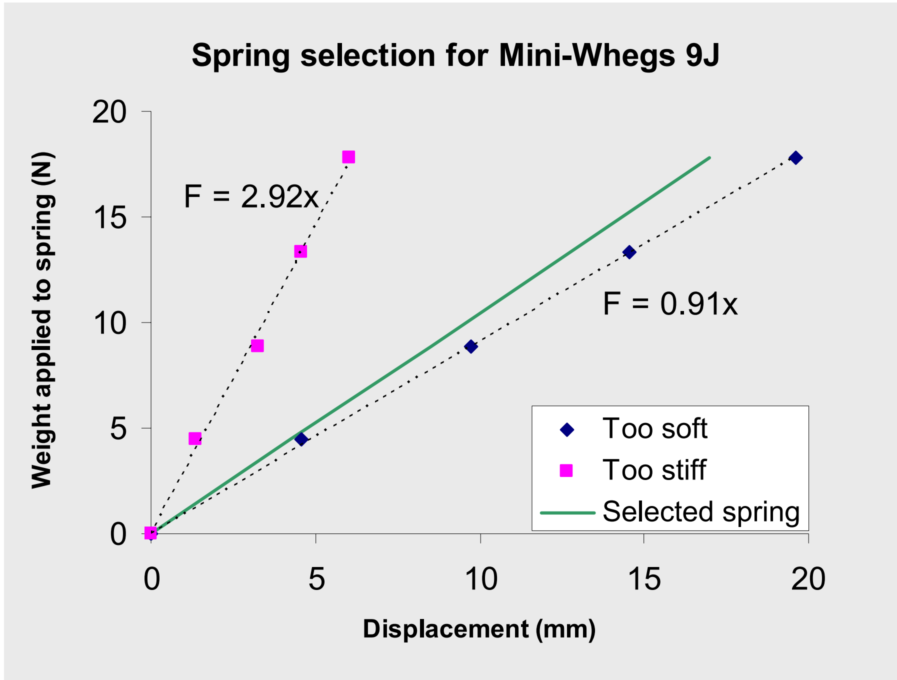


Figure 7.4 – Two springs from a random assortment were tested on the robot and then tested to find their stiffness. The spring which performed best on the robot has a stiffness of 1.05 N/mm.

7.4 Testing

While testing different springs to select the one which performed best, the ABS side rail of the robot cracked near the slip-gear mechanism. The high resistance from the stiff springs being tested caused the pinion and gear of the slip-gear to push away from each other. To remedy this undesirable situation, modifications were made to the design. First, the side rail was re-machined from Delrin®, which has much higher tensile strength than ABS. A few of the weight reducing holes in the side rail were also eliminated to remove stress concentrations. Secondly, a thin piece of Delrin® was machined which attaches to the transmission of the jumping motor with two mounting screws. This small brace also attaches to the jumping axle via a ball bearing. Thus, the small piece of Delrin® holds the motor and axle at a fixed distance, keeping the slip-gear engaged.

Figure 7.5 – Composite of video frames showing Mini-Whegs 9J easily clearing a 9cm barrier.

After reinforcing the frame, the best spring was remounted on the robot. Running and jumping were then recorded on video for further analysis. By moving different joysticks on the radio transmitter, the operator can easily control steering, running, and jumping independently. With the selected spring, the robot can jump as high as 18cm from the lowest point of the robot to the ground. By adjusting the speed of the robot on the approach to jumping, the jump trajectory can be controlled. For a more vertical jump, the robot should start standing still. For a forward and upwards trajectory, the robot should run while it jumps. Since the modes of locomotion are independent, either trajectory is easy to accomplish. When jumping over obstacles onto ground at the same level, the robot lands upright, eliminating the need for the operator to drive the robot into an obstacle to flip it over (Figure 7.5).

7.5 Discussion

The final Mini-Whegs 9J robot weighs 191g, much less than Mini-Whegs 6J, which weighed 294g. The lower weight and smaller chassis allow the robot to jump much more easily than the previous attempt at a fully controllable jumping robot. The robot has a top speed of 3.3 body lengths per second (26cm/s), which is about a third of the top speed of Mini-Whegs 5. The highest jump is 4cm lower than the highest jump of Mini-Whegs 4J. However, the target speed and jumping height set for Mini-Whegs 9J were met, so the combination of both modes of locomotion in the same robot can be considered a success. A goal for a future Mini-Whegs robot would be to improve performance in either mode of locomotion by incorporating different motors or power supplies to increase the power to weight ratio .

For future development, it would be worthwhile to do further research on available motors, transmissions, and other methods for winding the spring in the jumping mechanism. Theoretical calculations with manufacturer data for the chosen spring and transmission show that the torque on the transmission from the spring at its fully extended position (about 600mNm) meets or exceeds the maximum allowable torque for the transmission (Appendix D –). Winding of the spring is relatively quick, especially compared to Mini-Whegs 4J, so the reduced speed of a larger transmission would not be detrimental. However, no higher rated transmission in an appropriate size is available from Maxon, so a different manufacturer, customized transmission, or custom final transmission stage will be required for higher jumping.

Chapter 8 – Summary and Future Work

8.1 Summary

Mini-Whegs 4J successfully proves that a jumping capability can be added to a small robot to improve mobility and overcome obstacles of relatively large size. However, it does not include active control of the jumping mechanism. The robot jumps at regular intervals while running, which is not a useful design for actual terrain.

To prepare for the development of a complete running and jumping robot, robust and reliable components were designed and tested in Mini-Whegs 5. A simplified universal joint consisting of a ball and cup is used to create a strong and efficient steering mechanism. Mini-Whegs 5 can easily crawl over obstacles larger than the radius of its whegs, run at speeds up to 10 body lengths per second, and turn within a radius of 2.5 body lengths.

Mini-Whegs 6J was the first attempt at combining the successful features of Mini-Whegs 4J and Mini-Whegs 5 in the same robot. The resulting design is much larger and heavier than either previous robot individually.

Excess weight makes Mini-Whegs 6J too heavy to jump, so Mini-Whegs 7 was designed to reduce the weight of the Mini-Whegs platform. Mini-Whegs 7 weighs approximately a third as much as Mini-Whegs 6J. The use of an inexpensive servo for driving makes Mini-Whegs 7 very light, but also significantly slower than Mini-Whegs 5. Built for under $180, Mini-Whegs 7 can run at approximately 4 body lengths per second using the same batteries as Mini-Whegs 5.

Mini-Whegs 7 can also successfully carry payloads equal to its own weight or more. This makes the robot ideal as a starting point for the addition of a jumping mechanism similar to the one used on Mini-Whegs 4J. The final Mini-Whegs 9J robot weighs just 191g, less than Mini-Whegs 4J, and much less than Mini-Whegs 6J. The robot runs about as fast as Mini-Whegs 7 and can jump almost as high as Mini-Whegs 4.

8.2 Future Work

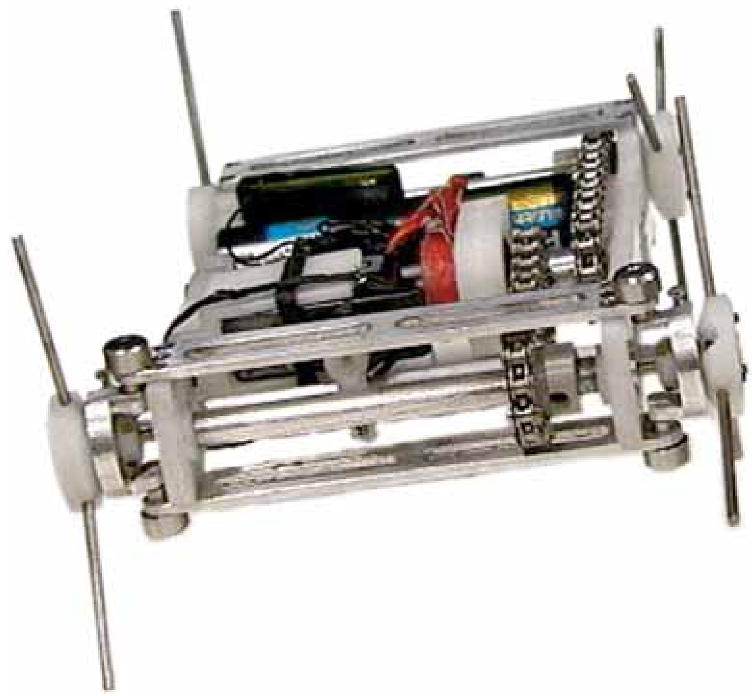
While Mini-Whegs 9J successfully proves that independent running and jumping can be accomplished in Mini-Whegs, there are some weaknesses in the design which could be improved upon. As discussed at the end of Chapter 7, the transmission used to wind the jumping spring is possibly too fragile for the large forces created by the spring. Research into stronger transmissions or alternative methods for retracting the jumping mechanism could lead to a robot that can jump higher without risk of damage to the components.

Some minor changes can be made in the design and manufacture of the chassis as well. The thin plastic components tend to vibrate during machining, sometimes creating cracks or punctures. By manufacturing the body shell using fused deposition modeling (FDM), vibrations could be avoided, leading to a stronger robot. Ideally, the robot parts could also be mass produced via plastic injection molding.

The most recent Mini-Whegs robots, Mini-Whegs 7, 8, and 9J, have fully enclosed bodies which help keep foreign particles out of the drive components of the robot. This greatly enhances their usefulness in outdoor environments. However, the design is currently not water-tight. Grease or O-ring tubing could possibly be used to seal a future robot to create a Mini-Whegs robot impervious to weather, or even a Mini-Whegs robot which can swim.

Mini-Whegs also provides a versatile platform for research involving sensor integration and robot group behavior as well as research in increased mobility. While much success has already been achieved, the possibilities for further improvement are endless.

Appendix A – Mini-Whegs Evolution



Name: Mini-Whegs 1

Built: July 2001 by Andrew Horchler

Size: 8.3cm long by 6.4cm wide by 2cm thick

Mass: 125g

Mini-Whegs 1 proved that whegs work at a small scale. It uses flexible couplings for steering and torsional compliance.

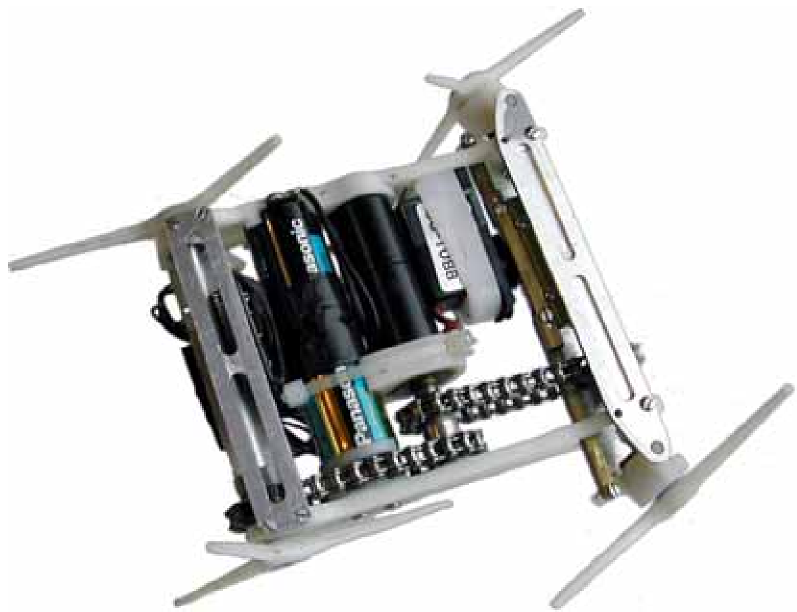
Name: Mini-Whegs 2

Built: November 2001 by Andrew Horchler

Size: 7.6cm long by 5.3cm wide by 1.7cm thick

Mass: 94g

Mini-Whegs 2 was a somewhat unsuccessful attempt at creating a smaller, lighter Mini-Whegs robot. The batteries selected were incapable of providing the current necessary to power the Maxon drive motor.



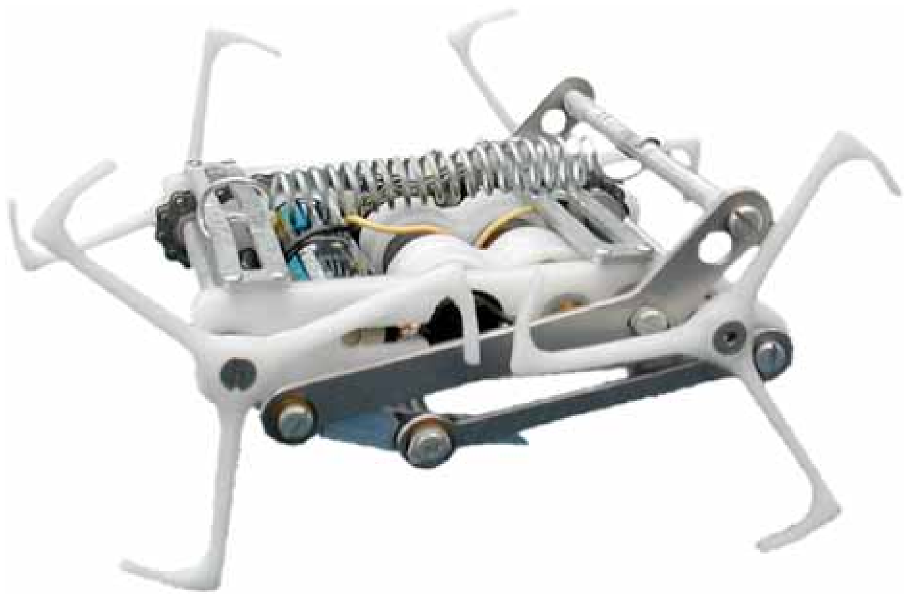
Name: Mini-Whegs 3

Built: February 2002 by Andrew Horchler

Size: 8.4cm long by 6.4cm wide by 2cm thick

Mass: 147g

Mini-Whegs 3 is an improved version of Mini-Whegs 1. Ball bearings and Delrin® whegs improve the performance over Mini-Whegs 1.



Name: Mini-Whegs 4J

Built: April 2002 by Jeremy Morrey

Size: 9.4cm long by 7.6cm wide by 2.4cm thick

Mass: 209g

Mini-Whegs 4J proves that jumping can be incorporated on a Mini-Whegs platform. It does not include any active control.

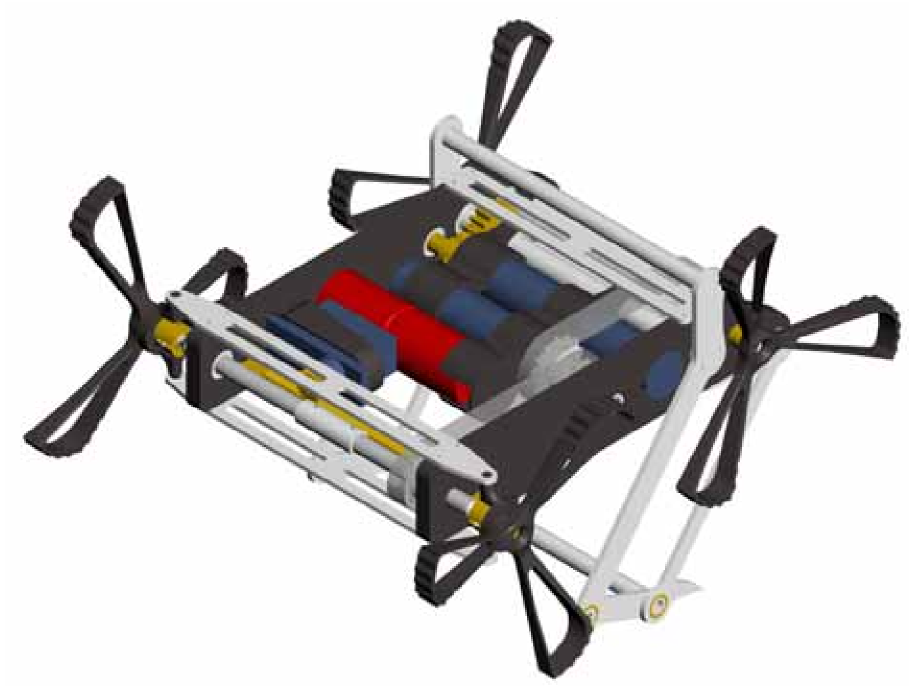
Name: Mini-Whegs 5

Built: July 2002 by Jeremy Morrey and Bram Lambrecht

Size: 9.1cm long by 6.9cm wide by 2cm thick

Mass: 165g

Mini-Whegs 5 is a robust platform with reliable ball and cup steering joints. Small feet on the whegs improve mobility.



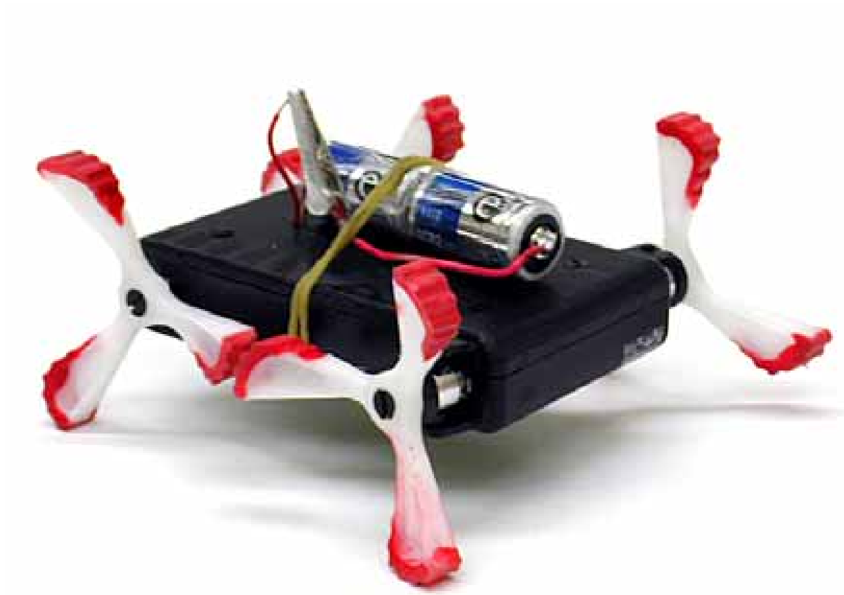
Name: Mini-Whegs 6J

Built: May 2003 by Jeremy Morrey and Bram Lambrecht

Size: 12.4cm long by 8.4cm wide by 2.5cm thick

Mass: 294g

Mini-Whegs 6J was an unsuccessful attempt at combining elements of Mini-Whegs 4J and 5. The robot is too large and heavy to run or jump well.



Name: Mini-Whegs 7

Built: October 2003 by Bram Lambrecht

Size: 8.9cm long by 5.4cm wide by 1.8cm thick

Mass: 89g (108g with CR2 batteries)

Mini-Whegs 7 is a smaller, fully enclosed Mini-Whegs robot. It uses many off-the-shelf components to reduce cost and weight.

Name: Mini-Whegs 8

Built: April 2004 by Andrew Schifle, Elizabeth Steva, and Bram Lambrecht

Size: 9.5cm long by 6.7cm wide by 1.8cm thick

Mass: 110g

Mini-Whegs 8 is a slightly larger version of Mini-Whegs 7 which encloses the batteries within the body of the robot.

Name: Mini-Whegs 9J

Built: June 2004 by Bram Lambrecht

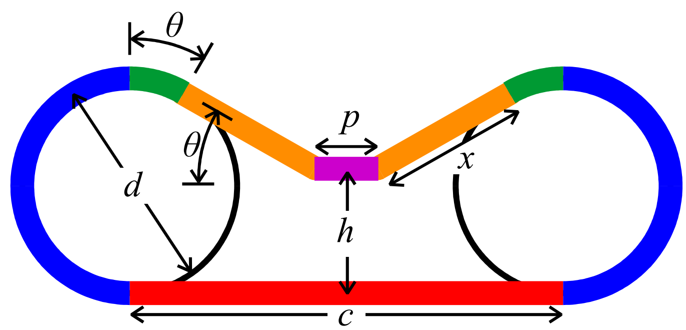
Size: 10.4cm long by 7.6cm wide by 2.1cm thick

Mass: 191g

Mini-Whegs 9J is a fully controllable running and jumping Mini-Whegs robot.

Appendix B – Calculations for the design of Mini-Whegs 6J

B.1 Chain Length Measurement



The sum of the vertical measurements is:

$$h + x \sin\theta + d/2\,(1 - \cos\theta) = d \quad (1)$$

The sum of the horizontal measurements is:

$$p + 2\,x \cos\theta + d \sin\theta = c \quad (2)$$

So, the total length of the chain is:

$$L = c + (\pi + \theta)\,d + p + 2\,x \quad (3)$$

The center distance *c*, pitch diameter *d*, and the chain pitch *p* are known; *h* is measured; and *x* and θ can be determined from equations (1) and (2).

B.2 Slip Gear Contact Ratio

To calculate the contact ratio between the slip gear and mate, the following formula is used:

$$CR = \frac{\sqrt{r_{ap}^2 - r_{bp}^2} + \sqrt{r_{ag}^2 - r_{bg}^2} - (r_p + r_g)\sin\phi}{p_b}$$

where r_p is half of the pitch diameter of the slip gear, r_g is half the pitch diameter of the mate, *P* is the diametrical pitch, and

$$r_{bp} = r_p \cos\phi,\; r_{bg} = r_g \cos\phi,\; r_{ap} = r_p + \frac{1}{P},\; r_{ag} = r_g + \frac{1}{P},\; p_b = \frac{\pi}{P}\cos\phi$$

Appendix C – Data for Mini-Whegs 7

The following tables provide data to support the results described for the miniature Mini-Whegs 7 robot in Chapter 6.

C.1 Approximate cost of components

The following table gives the cost of all the components and materials used in Mini-Whegs 7. The total is well within the target cost of $250.

Component	Manufacturer's description	Unit $	Quan.	Price
drive servo	MPI MX-50HP	$20.99	1	$20.99
steering servo	GWS Pico/BB	19.99	1	19.99
steering joint ball	Associated Factory Team Blue Aluminum Ball Studs (8 pack)	7.69	2	1.92
axle bearings	440C SS/ABEC 3 0.1875 Bore Plain Ball Bearing	5.43	6	32.58
drive shaft bearing	440C SS/ABEC 3 0.25 Bore Plain Ball Bearing	5.49	1	5.49
radio receiver	Hitec Feather 4-Channel FM Receiver	40.98	1	40.98
steering pinion	48 pitch 14.5° 16 tooth Nylon gear	1.93	1	1.93
steering rack	48 pitch 14.5° Nylon gear rack (1 foot)	2.46	3”	0.62
wheg screws	#4-40 5/16" Black Nylon flat machine screw (100 pack)	4.57	4	0.18
assembly screws	#2-56 3/8" Black Nylon flat machine screw (100 pack)	4.6	4	0.18
battery	Sanyo 6.0V Lithium L544	4.25	1	4.25

axle sprockets	0.1227 Pitch, 12 Tooth, 3/16" Bore roller chain sprocket	1.01	2	2.02
drive sprocket	0.1227 Pitch, 9 Tooth, 1/8" Bore roller chain sprocket	0.98	1	0.98
chain	0.1227 Pitch Acetal resin roller chain (1 foot, about 98 links)	8.04	58 links	4.76
steering rack pin	#0-80 3/8" SS pan head slotted machine screw (100 pack)	5.26	2	0.11
steering joint pin	0.045" Music Wire	12.23	1”	0.01
axles	Precision ground 3/16" 6061 Aluminum rod (6 feet)	30.20	5”	1.92
steering joint cup	5/16" 6061 Aluminum rod (6 feet)	4.94	2”	0.07
chassis	Black Delrin Sheet 1/2" Thick, 12"X12"	38.32	1	38.32
			Total (without shipping costs)	**$177.30**

C.2 Comparison of Maxon motor to MPI servo

The values in the following table are based on the manufacturers' specifications for the two motors. The MPI high power servo is model number MX-50HP, distributed by Maxx Products, Inc. Torque and speed numbers for the servo are rated at 4.8 Volts. The Maxon motor is an RE-13, 1.2 Watt, 2.4 Volt model number 118420 with a 67:1 model number 110315 metal planetary gear transmission. The speed figure based on the maximum allowable speed of the motor, and the maximum torque is based on the continuous rotation figure from the transmission specifications.

	MPI Servo	**Maxon Motor**
Speed (rpm)	125	189
Torque (mNm)	162	300
Starting current (mA)	300	1150
Mass (g)	9.1	32
Cost	$20.99	$107.40
Speed / Mass	1.00	0.43
Torque / Mass	1.00	0.53
Power / Mass	1.00	0.8
Power / Cost	1.00	0.55

Based on mass or cost value, the MPI servo has the obvious advantage.

C.3 Current draw for various operating conditions

The following gives the current draw of the robot for various operating conditions. These values were read from the analog indicator on the power supply used to run the robot for these tests. The results were identical with the drive components removed from the drive train. All measurements are ±10 mA.

Operating condition	Current draw (mA)
Continuous full forward	200
Continuous full reverse	170
Peak, stop to full forward	300
Peak, full forward to full reverse	350
Peak, full forward with steering	410
Peak, full reverse with steering	370

C.4 Top speed calculations

The top speed was measured by counting the number of video frames required for the robot to move between taped markings on the floor at one foot intervals. The number of frames was converted to a measurement in seconds. The mean of these values was calculated and converted to a measurement in body lengths per second. Here, the body length is the distance between the centers of the whegs.

	Single 6 Volt Cell	Two 3 Volt Cells
Number of samples	6	17
Mean time interval (s)	1.64	1.18
Standard deviation (s)	0.16	0.09
Speed (cm/s)	19 ± 2	26 ± 2
Speed (body len./s)	2.7 ± 0.3	3.8 ± 0.3

Appendix D – Torque Considerations in Mini-Whegs 9J

Maxon transmissions are rated for a maximum output torque by the manufacturer. For the selected GP13 1119:1 transmission, model number 110317, the maximum allowed continuous torque load is 350mNm, and the maximum allowed intermittent torque is 530mNm. The RE13 2.5W motor, model number 118485, attached to the transmission has a stall torque of 9.14mNm. The maximum efficiency of the transmission is 62%, so if the input torque is the stall torque of the motor, then the output torque of the transmission will be $9.14\times1119\times0.62 = 6340$mNm. Thus, if the load on the transmission exceeds the rated torque, the motor can easily damage the transmission.

In Mini-Whegs 9J, the selected spring has a free length of 3.18cm and a spring constant of 1.05N/mm. The preloaded length of the spring is 4.80cm, and the maximum stretched length is 8.00cm. Thus, the spring nominally pulls the jumping mechanism leg with a force of $(8.00\text{cm}-3.18\text{cm})\times10.5\text{N/cm} = 53.7\text{N}$. The lever arm of the mechanism is 2.16cm long, and the gear reduction at the slip-gear is 2:3. If the efficiency of the slip-gear is assumed to be 80%, then the torque on the transmission output shaft from the spring force is $53.7\text{N}\times21.6\text{m}\times2/3\times0.80 = 619\text{mNm}$. This torque is unfortunately greater than the rated torque of the transmission! However, the spring used is operating outside of its rated range as well (maximum load 25.4N), so it may not actually be exerting the full 53.7N. Regardless, there is little if no safety factor for the operation of the transmission, so a solution rated for higher loads is highly desirable.

Bibliography

Allen, T.J. (2004). "Abstracted Biological Principles and Reduced Actuation Applied to the Design of a Walking Vehicle." Master of Science thesis. Cleveland, Ohio: Case Western Reserve University.

Althof, C.P. (2002). "Manufacturing Optimization of the Mini-Whegs Robots." Undergraduate senior project. Cleveland, Ohio: Case Western Reserve University.

Bittle, J., Cullen, C. (2004). "Mini-Whegs Leg Design." EMAE283 Undergraduate research project. Cleveland, Ohio: Case Western Reserve University.

Burrows, M. (2003). "Biomechanics: Froghopper insects leap to new heights." *Nature.* Vol. 424: 509.

Burrows, M., Morris, O. (2002). "Jumping and kicking in bush crickets." *Journal of Experimental Biology.* Vol. 206: 1035-1049.

Full, R. J., Tu, M. S. (1991). "Mechanics of a Rapid Running Insect: Two-, Four-, and Six-legged Locomotion." *Journal of Experimental Biology.* Vol. 156: 215-231.

Johnson, D. (2002). "Redesign and Improvement of Jumping Mini-Whegs." Undergraduate senior project. Cleveland, Ohio: Case Western Reserve University.

Kim, S., Clark, J.E., Cutkosky, M.R. (2004). "iSprawl: Autonomy, and the Effects of Power Transmission." *Proceedings of the Climbing and Walking Robots Conference* (CLAWAR '04). Madrid, Spain.

Lambrecht, B.G.A., Horchler, A.D., Morrey, J.M., Ritzmann, R.E., Quinn, R.D. (in press). "A Series of Highly Mobile and Robust Small Quadruped Robots." *Robotics and Autonomous Systems*.

Martin-Alvarez, A., de Peuter, W., Hillebrand, J., Putz, P., Matthyssen, A., de Weerd, J.F. (1996). "Walking Robots for Planetary Exploration Missions." *Proceedings of the Second World Automation Congress* (WAC '96). Montpellier, France.

Morrey, J.M. (2003). "Increasing Small Robot Mobility via Abstracted Biological Inspiration." Master of Science thesis. Cleveland, Ohio: Case Western Reserve University.

Morrey, J.M., Lambrecht, B., Horchler, A.D., Ritzmann, R.E., and Quinn, R.D. (2003) "Highly Mobile and Robust Small Quadruped Robots." *Proceedings of the IEEE International Conference on Intelligent Robots and Systems* (IROS '03). Las Vegas.

"Leaping into the Future: One Hop at a Time." NASA Press Release, November 28, 2000. Accessed July 31, 2004. http://www.jpl.nasa.gov/releases/2000/frog.html

Quinn, R.D., Nelson, G.M., Bachmann, R.J., Kingsley, D.A., Offi, J., Ritzmann, R.E. (2001). "Insect Designs for Improved Robot Mobility." *Proceedings of the Climbing and Walking Robots Conference* (CLAWAR '01). Karlsruhe, Germany.

Quinn, R.D., Kingsley, D.A., Offi, J.T., Ritzmann, R.E. (2002). "Improved Mobility Through Abstracted Biological Principles." *Proceedings of the IEEE International Conference on Intelligent Robots and Systems* (IROS '02). Lausanne, Switzerland.

Quinn, R.D., Allen, T.J., Bachmann, R.J., Ritzmann, R.E. (2003) "Abstracted Biological Principles Applied with Reduced Actuation Improve Mobility of Legged Vehicles." *Proceedings of the IEEE International Conference on Intelligent Robots and Systems* (IROS '03). Las Vegas.

"Sandia hoppers leapfrog conventional wisdom about robot mobility." Sandia National Laboratories Press Release, October 17, 2000. Accessed July 31, 2004. http://www.sandia.gov/media/NewsRel/NR2000/hoppers.htm

Saranli, U., Buehler, M., Koditschek, D., (2000). "Design, Modeling and Preliminary Control of a Compliant Hexapod Robot." *Proceedings of the IEEE International Conference Robotics and Automation* (ICRA '00), San Francisco, California.

Saranli, U., Buehler, M., Koditschek, D. (2001). "RHex a Simple and Highly Mobile Hexapod Robot." *International Journal of Robotics Research*, Vol. 20(7): 616-631.

Schifle, A., Steva, E. (2004). "Mini-Whegs Reloaded." Undergraduate senior project. Cleveland, Ohio: Case Western Reserve University.

Stoeter, S.A., Rybski, P.E., Gini, M., Papanikolopoulos, N. (2002). "Autonomous Stair-Hopping with Scout Robots." *Proceedings of the IEEE International Conference on Intelligent Robots and Systems* (IROS '02). Lausanne, Switzerland.

Watson, J.T., Ritzmann, R.E., Zill, S.N., Pollack, A.J. (2002) "Control of Obstacle Climbing in the Cockroach, *Blaberus discoidalis*: I. Kinematics." *Journal of Comparative Physiology.* Vol. 188: 39-53.

Wilson, D. M. (1966). "Insect Walking." *Annual Review of Entomology.* Vol. 11: 103-123.

Zeglin, G., Brown, H.B. Jr. (2002) "First hops of the 3D Bow Leg." *Proceedings of the Climbing and Walking Robots Conference* (CLAWAR '02). Paris, France.