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BIOLOGICALLY-INSPIRED MICRO-ROBOTS:

Volume 3, Micro-Robot Based On Abstracted Biological Principles

by

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14. ABSTRACT

This is one of three reports on the study of micro-robots. This document describes the development of novel highly mobile small robots called "Mini-Whegs" TM that can run and jump. They are derived from our larger Whegs series of robots, which benefit from abstracted cockroach locomotion principles. Key to their success are the three-spoke appendages, called wheel-legs, which combine the speed and simplicity of wheels with the climbing mobility of legs. Mini-Whegs use four wheel-legs to run in an alternating diagonal gait. These approximately 3-inch-long robots can move at sustained speeds of over 10 body lengths per second and can run over obstacles that are taller than their leg length. They can run forward and backward, and on either side. Their robust construction allows them to tumble down a flight of stairs with no damage and carry a payload equal to twice their weight. A jumping mechanism has also been developed that enables Mini-Whegs to surmount much larger obstacles such as stair steps.A second report (NATICK/TR-05/010) focuses on robots based on crickets, and a third (NATICK/TR-05/011) focuses on the investigation of a micro-joint angle sensor using MEMS Cilia.

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GAIT
SPEED
SMALL
ROBOTS
UNEVEN
WHEELS
CLIMB
TERRAIN
MOBILITY
SIMPLICITY
OBSTACLES
APPENDAGES
LOCOMOTION
DIAGONAL GAIT
IMPLEMENTATION
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PREFACE

This report outlines the research undertaken by Case Western Reserve University, Cleveland, OH, and Carnegie Mellon University, Pittsburgh, PA to develop micro-robots and the components needed to fabricate those micro-robots. Two types of robots, each 3 inches long, resulted from this work along with several important components. This report is presented in three volumes: The first volume describes the development of a robot based upon a cricket; the second volume describes the development of microelectromechanical systems (MEMS) joint angle sensors based upon cilia; the third volume describes another type of robot that can run faster than any other legged vehicle of its size, run over relatively large obstacles, and operate for several hours without a change of batteries. The purpose of this report is to communicate the design, implementation and evaluation of these unique micro-robots and their essential components. The project was completed during the period June 1998 to September 2002 under contract number C-DAAN02-98-C-4027, under the direction of U.S. Army Research, Development and Engineering Command, Natick Soldier Center, Natick, MA, and sponsorship of the Defense Advanced Research Projects Agency (DARPA), Arlington, VA.

This report is one of a series of three. The references for the other reports are:

Quinn, R., Ritzmann, R., Phillips, S., Beer, R., Garverick, S., and Birch, M. (2005) *Biologically-Inspired Micro-Robots: Vol. 1, Robots Based on Crickets,* Technical Report, (NATICK/TR-05/010), U.S. Army Research, Development and Engineering Command (RDECOM), Natick Soldier Center, Natick, MA 01760.

Fedder, Gary K., and de Rosset, Lauren Elizabeth. (2005) *Biologically-Inspired Micro-Robots: Vol.2, Investigation of a Micro-Joint Angle Sensor Using MEMS Cilia,* Technical Report, (NATICK/TR-05/011), U.S. Army Research, Development and Engineering Command (RDECOM), Natick Soldier Center, Natick, MA 01760.

BIOLOGICALLY-INSPIRED MICRO-ROBOTS
Volume 3, Micro-Robots Based On Abstracted Biological Principles

SUMMARY

This is the third of three volumes describing the work performed in the Biologically-Inspired Micro-Robots project. The overall goal of the project was to develop legged vehicles that can run and jump and that can fit in a 2-inch cube. In Volume 1 small robots based upon crickets are described. To support this effort it was necessary to advance component technologies such as artificial muscles, micro-actuators, micro electro-mechanical system (MEMS) valves and small compressors. Volume 2 describes the development of joint-angle sensors for micro-legged robots using MEMS fabrication processes. This report, Volume 3, describes the development of micro robots that can run and jump based upon more abstracted biological principles.

This volume of the report describes the development of novel, highly mobile small robots called "Mini-Whegs™" that can run and jump. A series of five Mini-Whegs™ robots have been constructed, each one representing an advancement of the concept. They are derived from our larger Whegs™ series of robots, which benefit from abstracted cockroach locomotion principles. Key to their success is the three-spoke appendages, called wheel-legs, which combine the speed and simplicity of wheels with the climbing mobility of legs. Mini-Whegs™ uses four wheel-legs to run in an alternating diagonal gait. These approximately 3-inch long robots can move at sustained speeds of over 10 body lengths per second and can run over obstacles that are taller than their leg length. They can run forward and backward, and on either side. Their robust construction allows them to tumble down a flight of stairs with no damage and carry a payload equal to twice their weight. A jumping mechanism has also been developed that enables Mini-Whegs™ to surmount much larger obstacles such as stair steps.

1. INTRODUCTION

1.1 Introduction and Motivation

A variety of robots similar in size to the vehicles described in this volume have been developed, but the majority of them are limited in mobility. For example, because Khepera robots have a 5cm wheelbase and 1.4cm diameter wheels [11], they can move only on very smooth, flat surfaces. The robots in the Alice series use large wheels relative to the size of the robots for improved mobility, but they still suffer from the limitations of wheels on complex terrain [4]. For example, without complicated suspensions, wheeled robots cannot generally climb obstacles of heights greater than the radius of the wheels. The Scout series of robots also uses relatively large diameter wheels for their size, and some versions have a separate mechanism that enables them to jump up a stair or use expanding wheels to overcome larger obstacles [6]. Millibots use tracks but it is not clear that at this scale they offer much of an advantage [1]. Fukui et al. developed a small hexapod robot that uses piezoelectric actuators to run in a tripod gait [7]. The vehicle is limited to operating on relatively flat surfaces because its legs have short ranges of motion.

It is difficult for small robots to move through real-world terrain simply because of the relative size of the obstacles they must overcome. Therefore, it is particularly important for small robots to use efficient locomotory appendages. For a given vehicle size, legs promise the greatest mobility because they enable discontinuous contact with the substrate, which is important for uneven terrain. Insects are excellent examples of highly mobile legged vehicles, and therefore a robot designer would be well advised to draw inspiration from them.

The design of the slightly larger Sprawlita [5] was inspired by the cockroach. It is a 16cm hexapod that uses a combination of servomotors and air cylinders for locomotion. Its top speed of 4.5 body lengths per second is very fast as compared to existing robots, but it is not power autonomous and because it uses 6 bars of air pressure it is unlikely to become so. Volume 1 of this series describes the development of a 7.5cm long hexapod inspired by the cricket and it is actuated by McKibben artificial muscles [2]. Because it walks using only 2 bars of air pressure, it can be made power autonomous.

Our laboratory is dedicated to the advancement of the field of robotics using insights gained through the study of natural organisms. Biological inspiration can be implemented in varying degrees from the direct to the abstracted [16]. Robots designed with the direct approach use analyses of the morphology and motion of the animals themselves. This approach sometimes requires that new technologies be developed, whereas abstracted locomotion principles can often be implemented using current technology. Robots such as R3, R4 [15] aim to achieve high levels of mobility using control and design ideas inspired by the *Blaberus discoidalis* cockroach. The design and control of these robots represents a complex, relatively long-term research project. On the other end of the spectrum are the robots inspired by abstracted biological principles, such as the Mini-Whegs™ robot series presented in this volume. These robots are designed to take advantage of certain biological principles and mechanisms, while applying existing technology to create much simpler robots over a shorter research timeframe.

1.2 The Whegs™ Concept

Previous legged robots have been designed to navigate difficult terrain. These robots have, for the most part, been slow and complicated due to the challenge of actuating multiple joints. Conventional wheeled vehicles can move quickly on smooth, hard substrates, but their mobility is challenged by obstacles of height on the order of the radius of their wheels. Suspension systems such as the "rocker bogey" reduce this limitation, but with the disadvantage of additional complexity.

Other researchers have explored vehicle designs that use a combination of wheels and legs, but many still involve significant complication. Saranli et al. developed the simplified hexapod "RHex" [18]. Each leg is a single spoke that rotates in a circular motion. It uses one motor to drive each leg. In 2001, we proposed the idea of a more simplified hexapod robot, which was meant to take advantage of the characteristics of both wheels and legs and use abstracted cockroach locomotion principles to great effect. This "Whegs™" concept uses multiple spokes fixed to a rotating hub. The spokes or legs provide a high degree of mobility, while the rotational motion of wheels contributes to speed and simplicity. A main advantage of this design is that it requires only one motor to drive all six legs.

Three-spoke wheel-legs were chosen as a compromise between climbing ability and smooth ride. The spokes of each wheel-leg are spaced 120 degrees apart and two wheel-legs are mounted on each axle. Contralateral pairs of wheel-legs are nominally positioned 60 degrees out of phase with each other. Whegs™ wheel-legs were first implemented in the 20 inch long Whegs™ Series robots, which have a total of three axles, each 60 degrees out of phase with its neighbor. One motor drives all three axles via chains and sprockets so that Whegs™ robots nominally walk in a cockroach-like alternating tripod gait.

Whegs™ robots also have compliant mechanisms in their axles that enable the two wheel-legs on each axle to passively change their relative phase by as much as 60 degrees [15]. A key element to the robots' success, these passive "preflexes" allow gait adaptation in response to different terrain [12] in a manner similar to the movements of a cockroach [20]. This ability enables Whegs™ to simultaneously apply force and climb with contralateral legs in phase to surmount an obstacle, with no active control intervention (see Figure 1-1).

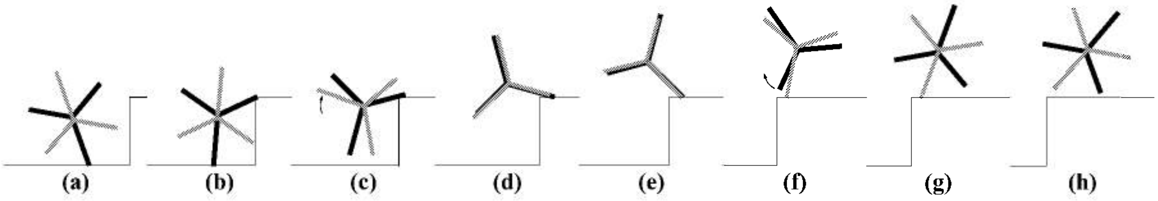


Figure 1-1. Illustration of the Whegs™ concept: a) **the two front wheel-legs of the robot approach an obstacle;** b) **the far (black) wheel-leg makes contact first, and** c) **while the far**

wheel-leg is slowed, passive torsional compliance in the drive train allows the near (gray) Wheg™ to rotate into phase with the far wheel-leg; d) **once in phase, the two wheel-legs can** e) **propel the front of the robot over the obstacle;** f) **atop the obstacle the two wheel-legs separate and** g) **spring back to their** h) **prior configuration.**

The relatively large (6 lbs., 20" long) Whegs™ I hexapod prototype demonstrated the potential of the Whegs™ concept (see Figure 1-2). It was constructed using a single motor, off the shelf radio controlled car components, and a custom machined chassis of Delrin and aluminum. Steering was accomplished using both front and rear electrically coupled servo actuation, similar to the front wheel steering mechanism of an RC car. At 3 body lengths per second, Whegs™ I moved several times faster than other legged robots [10], and could climb obstacles higher than the top of the robot chassis, or 1.5 leg lengths tall. The success of this prototype spurred future work on the large Whegs™ series robots, and inspired the more compact Mini- Whegs™ design.

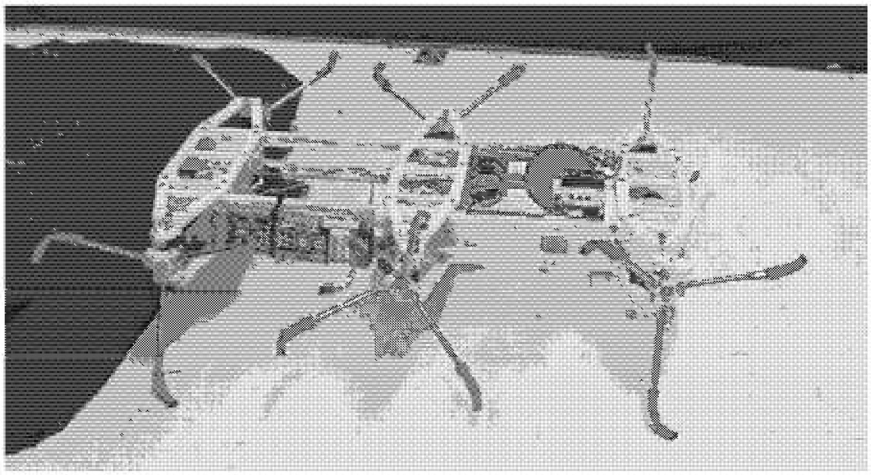


Figure 1-2. Whegs™ I uses a single drive motor to drive all six appendages.

This volume describes the development of novel small robots called Mini- Whegs™ that are highly mobile, robust, and power autonomous. Their basic design is derived from the Whegs™ concept, but modifications were made to reduce size and improve mobility. The robots have performance goals of high speed, obstacle climbing ability, and versatility. The overall design goals for the Mini- Whegs™ vehicles are simplicity, compactness, and durability, achieved over a relatively short development period. The designs currently use simple remote control (RC) and are meant to develop the mechanical functionality of the Mini- Whegs™ platform. However, autonomous and computer control have been tested in several forms and are part of the natural future progression of the Whegs™ and Mini- Whegs™ robots.

Mini- Whegs™ is an attempt to implement abstracted biological principles on a miniature (less than 10cm) scale. The basic design is derived from the Whegs™ concept, with modifications to reduce size and improve relative mobility. The first three robots in the series, Mini- Whegs™ 1, 2, and 3, are documented in Section 2. The remainder of this volume details the design and performance of the newest robots in the series, Mini- Whegs™ 4J and 5. Conclusions are drawn and future opportunities are outlined in Section 6.

2. INITIAL MINI-WHEGS™ DEVELOPMENT

2.1 The Mini-Whegs™ Robots

To date, five Mini-Whegs™ robots have been built (Figure 2-1). This section summarizes the concept, design, and performance of the three initial robots in the Mini-Whegs™ series. Mini-Whegs™ 1 was designed and built in the summer of 2001 and is approximately 2.5" x 3.25" and weighs 125g. It was constructed using aluminum, Delrin and miniature RC components, and proved solid and reliable. With Mini- Whegs™ 2, we attempted to create an even smaller and lighter version of the robot, constructed almost entirely out of Delrin for a weight of 94g. Mini-Whegs™ 3 returned to the basic design of MW-1, with many incremental improvements in design and performance.

A summary of the progression and primary features of all Mini- Whegs™ robots is provided in Table 1. Names of the robots are abbreviated "MW" followed by a number designation. Design progression of the individual systems and components in Mini- Whegs™ 1, 2 and 3 comprises the remainder of this section.

Table 1. Mini-Whegs™ Vehicle Specifications

Name	Mini-Whegs 1 (MW-1)
Date	Jul-01
Dimensions	3.25 in. long, 2.5 in. wide, 0.8 in. high
Mass	125 g
Steering	Flexible coupling – spring tubing, servo arm actuation
Wheg style	Steel and Delrin, 1.3 in. radius, pointed feet
Other	Chain drive, CR2 batteries, Delrin and aluminum frame, integrated sub-micro receiver/speed controller

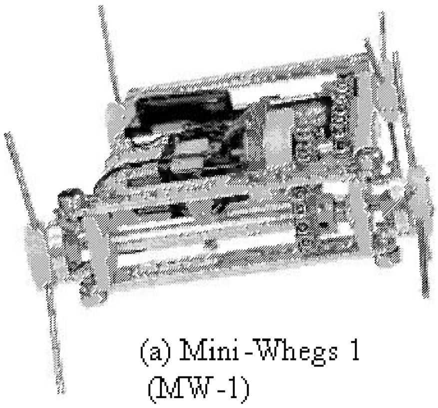
Table 1. Mini-Whegs™ Vehicle Specifications (Cont'd)

Name	Mini-Whegs 2 (MW-2)
Date	Nov-01
Dimensions	3.0 in. long, 2.1 in. wide, 0.675 in. high
Mass	94 g
Steering	Living universal joint, rack and pinion actuation
Wheg style	Single piece Delrin, 1.3 in. radius, pointed feet
Other	Timing belt drive, 1/3N batteries, all Delrin frame, integrated sub-micro receiver/speed controller

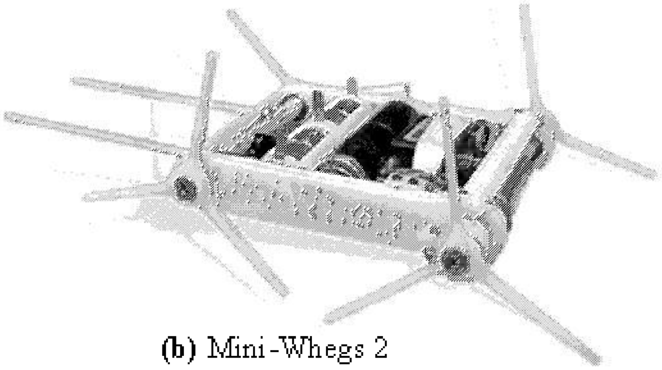
Name	Mini-Whegs 3 (MW-3)
Date	February 2002, steering retrofit August 2002
Dimensions	3.3 in. long, 2.5 in. wide, 0.8 in. high
Mass	147 g (including new steering mechanism)
Steering	Flexible coupling – spring tubing, servo arm
Wheg style	Single piece Delrin, 1.4 in. radius, pointed feet
Other	Chain drive, CR2 batteries, Delrin and aluminum frame, integrated sub-micro receiver/speed controller

Name	Mini-Whegs 4J (MW-4J)
Date	Apr-02
Dimensions	3.7 in. long, 3.0 in. wide, 0.95 in. high
Mass	209 g
Steering	None – left out for simplicity
Wheg style	Single piece Delrin, 1.4 in. radius, rounded arc feet
Other	Chain drive, CR2 batteries, modified frame, automatic repeating jump mechanism, no radio control

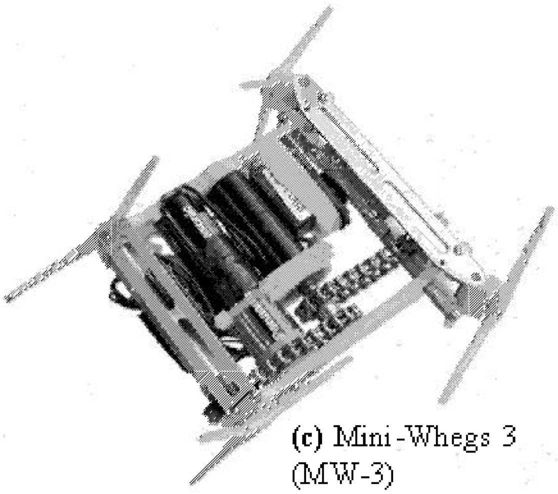
Name	Mini-Whegs 5 (MW-5)
Date	Jul-02
Dimensions	3.6 in. long, 2.7 in. wide, 0.8 in. high
Mass	165 g
Steering	Ball and cup universal, rack and pinion actuation
Wheg style	Single piece Delrin, 1.4 in. radius, rounded arc feet
Other	Chain drive, CR2 batteries, snap-in battery holder, separate sub-micro bi-directional speed controller



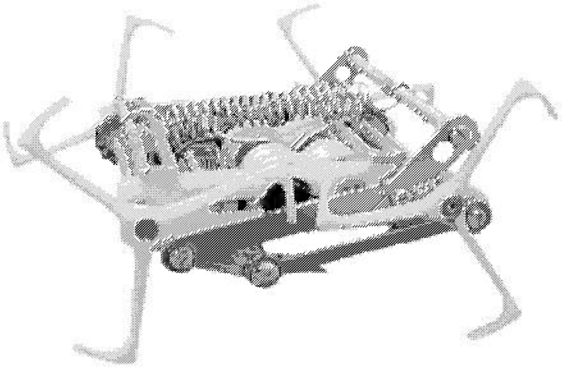
(a) Mini-Whegs 1
(MW-1)



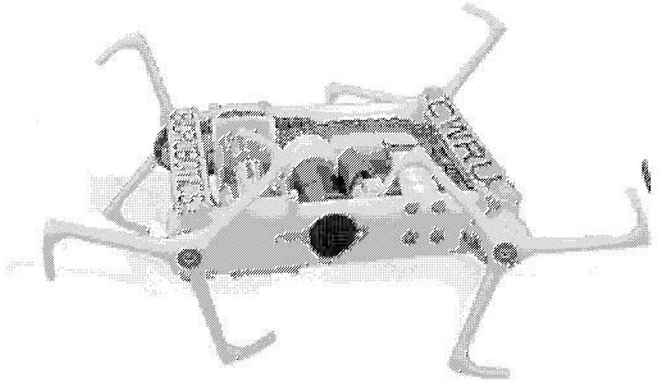
(b) Mini-Whegs 2
(MW-2)



(c) Mini-Whegs 3
(MW-3)



(d) Mini-Whegs 4J
(MW-4J)



(e) *Mini-Whegs 5*
(MW-5)

Figure 2-1. Five generations of Mini-Whegs™ robots (not to scale).

2.2 Mini-Whegs™ Design

All Mini- Whegs™ robots are similar in size and weight, and have two axles with two three-spoke wheel-legs each. A single propulsion motor drives both axles in a nominal alternating diagonal gait and the front wheel-legs are steered with a single servo. The chassis consists of a rectangular frame that houses the main systems, including the drive train, steering components, batteries and the onboard RC components. Each of these basic systems has evolved and improved over the progression of robots, from Mini- Whegs™ 1 to Mini- Whegs™ 5. Frame dimensions are approximately 3" long by 2.5" wide by 0.8" thick (7.5 x 6.8 x 2.0cm) with attached 1.6" (4.1cm) radius wheel-legs and an average mass of approximately 130g including batteries.

2.2.1 Whegs™ Wheel-Leg Appendages

As described in Section 1, Whegs™ wheel-leg appendages provide a unique combination of speed and mobility. This concept, first demonstrated in the full sized Whegs™ I robot, was ideal for implementation in a small robot. Wheel-leg size was scaled down relative to chassis size and varies slightly between each robot; in essence, the largest possible wheel-legs were mounted so as to not interfere with each other, thereby allowing significant ground clearance and obstacle climbing ability. Mini- Whegs™ 1 has wheel-legs made with steel spokes mounted in a Delrin hub, as seen in Figure 2-2. Each front hub is fixed to the central axle through a flexible coupling system made from surgical spring tubing, allowing for a limited amount of torsional compliance between the axle and wheel-legs The system works as desired to allow for passive gait adaptation (Figs. 2-4 and 2-5) similar in concept to that on the full-sized Whegs™ robots, but the coupling is subject to failure under load. The rigid wheel-legs (Figure 2-2) are made from steel and Delrin, consist of 12 components each, and are complicated to machine and assemble.

The wheel-legs of Mini-Whegs™ 2 are instead machined entirely out of a single piece of Delrin (Figure 2-3). The material properties and slender leg design allows for a certain amount of compliance under normal operation, which provides a smoother ride. Instead of a spring coupling as in Mini-Whegs™ 1, a slender Delrin rod transfers power from the axle to the wheel-legs. This change removes some torsional compliance, but little change in obstacle surmounting ability is observed. The wheel-legs of MW-3 are the same as those used on MW-2, but different materials were used to provide torsional compliance within the axle connection.

An interesting phenomenon may be observed with these first two versions of the small wheel-leg design. Both used a sharp tipped foot, which penetrated carpet and other yielding surfaces to provide good traction. However, this foot sometimes snagged on the substrate and, because of the momentum and high power to weight ratio of the robot, caused the vehicle to somersault into the air (Figure 2-6). This behavior is undesirable because it makes operation of the robot less consistent. Solutions to these issues were proposed with the next Wheel-leg design and implemented in the construction of MW-5 (Section 4).

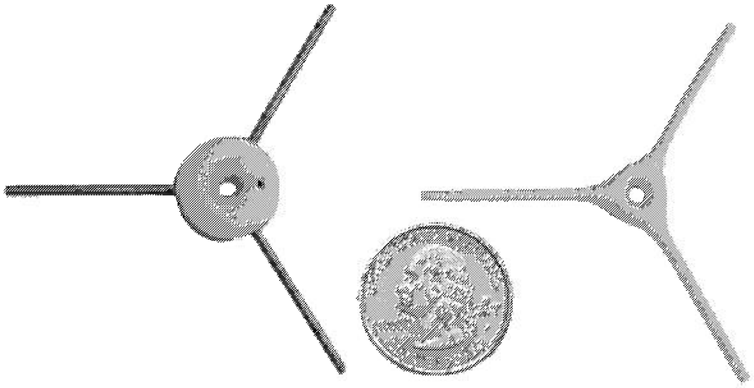


Figure 2-2. **Whegs™ appendage (version 1)** **Figure 2-3**. **Whegs™ appendage (version 2)**

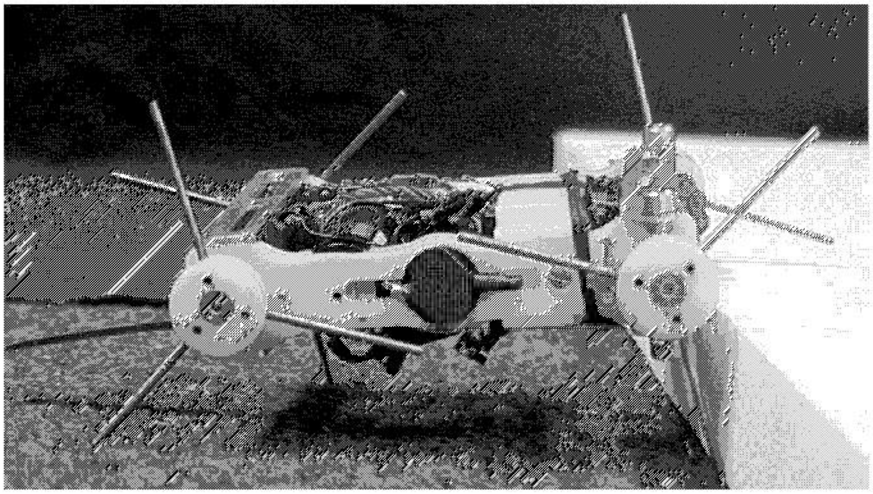


Figure 2-4. **Mini-Whegs™ 1 climbing – legs out of phase.**

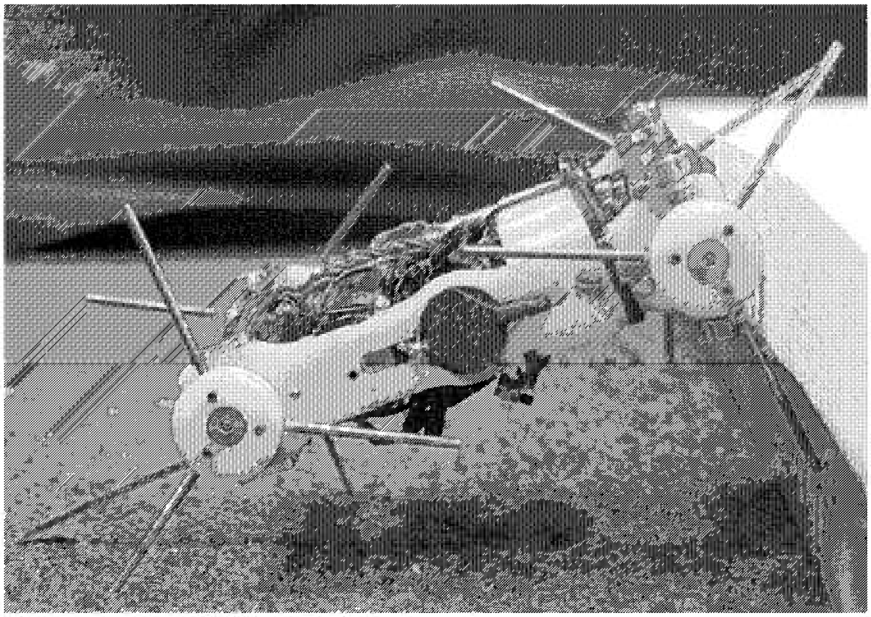


Figure 2-5. **Mini-Whegs™ 1 climbing – legs in phase.**

Figure 2-6. **Sequence of video frames showing Mini-Whegs™ skipping.**

2.2.2 Steering

The basic design of the steering mechanism for Mini-Whegs™ is similar to the system in an automobile. Each front Wheel-leg rotates in a bearing, which is supported by a steerable hub. A servo actuated sliding bar (MW-1) or rack (MW-2, 3, 5) connects to the steerable hubs with a slot and pin. The hubs pivot in mountings on the aluminum chassis cross braces to provide a steering motion. A rendering of the steering layout for Mini-Whegs™ 1 is shown in Figure 2-7.

Since all four wheel-legs are driven, the front axle must transmit power to the wheel-legs and still allow for steering movement. Flexible materials were explored for this application in MW-1, 2 and 3. As discussed in the Whegs™ design section, these components were designed to serve the dual purpose of providing torsional compliance for automatic gait adaptation. Mini-Whegs™ 1 uses a flexible spring coupling (Figure 2-7) to transmit torque from the axle to the wheel-leg and allow steering movement. However, the springs can fail under load. Mini-Whegs™ 2 uses a miniature living universal joint constructed by notching a Delrin rod. Two perpendicular sets of notches allow the rod to bend with two degrees of freedom while a slender section of material allows for some torsional compliance. In an attempt to create a more durable joint, Mini-Whegs™ 3 uses a spring with monofilament core and surrounding plastic tube. This composite member is intended to keep the spring from unwinding outward or collapsing inward. The interior core allows the spring to be firmly clamped with setscrews in an aluminum housing. Unfortunately, compliance is difficult to predict, and the flexible components quickly deteriorated in each of the designs. Later Mini-Whegs™ versions, including MW-5, forgo axle-based torsional compliance for greater precision and strength, as discussed in Section 5.

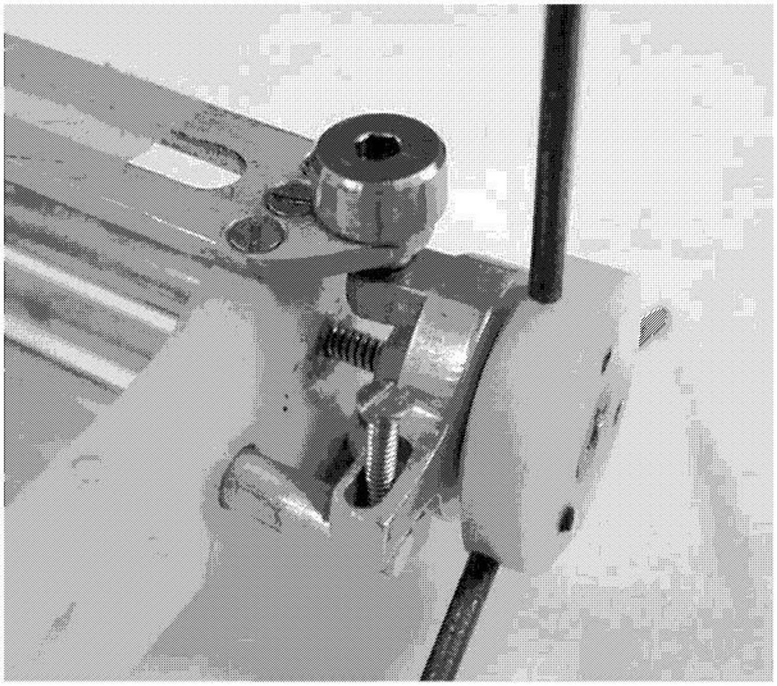


Figure 2-7. Steering mechanism layout for Mini-Whegs™ 1.

2.2.3 Chassis and Drive Train

The rectangular frames of the different Mini-Whegs™ vehicles have many similarities. Each frame contains a single drive motor, drive train, steering components, batteries and control system. To supply the desired high power and torque, a 13mm 1.2 W Maxon motor with attached 67:1 planetary transmission was chosen. The frame itself consists of two Delrin side rails with aluminum cross-braces (Delrin in MW-2) on the top and bottom. The side rails are precisely machined to support nearly every component inside the robot, including axle bearings, motor mounts, battery supports, and the steering servo and rack.

Mini-Whegs™ robots have two axles connected to the drive motor via non-slipping 0.1475" (0.375cm) pitch stainless steel drive chains. This non-slipping drive connection is necessary because the correct phase offset between front and rear axles must be maintained in order to achieve a nominal alternating diagonal gait. The use of chain drive and one motor to propel the robot has the additional advantage that all of the onboard power can be delivered to a single Wheel-leg if the others lose traction.

Made almost entirely of resilient Delrin, Mini-Whegs™ 2 (see Figure 2-1b) has several unique design features. It is a highly compact design at only 2.1"x3.0" and weighing 94g. The frame is constructed entirely of interlocking Delrin supports rather than aluminum cross-braces. The smallest available components were used, including miniature lithium batteries. Instead of steel chain, a lighter and more compact timing belt is substituted. Unfortunately, performance of this particular robot was limited due to poor performance from the batteries and drive train.

2.2.4 Control System and Operation

Figure 2-8 shows the underside of Mini-Whegs™ 3 and the layout of its components. Control of Mini-Whegs™ robots, except MW-4J (Section 4), is accomplished via a standard four-channel FM RC transmitter (Hitec Focus 4) and a unique sub-micro four-channel receiver. The receiver used for MW-1, 2, and 3, is a Sky Hooks & Rigging RX72-HYB, and has an integrated unidirectional speed controller. Though this component limits the robots to forward motion only, the receiver is extraordinarily compact at 0.0938" x 0.75" x 0.25 and 3.3 grams (Figure 2-9). A Cirrus CS-10BB or equivalent GWS Pico BB sub-micro servo weighing only 6 grams and rated for a maximum torque of 10 in-oz is used to actuate the steering motion. Because of their straightforward designs, Mini-Whegs™ robots are easy to operate. A small switch turns on the robot and a radio control transmitter is then used to control steering and throttle. The robots can function when inverted, though control becomes less intuitive. In Section 5, component variations are explored to provide bi-directional throttle control.

Mini-Whegs™ 1 and 2 can make use of removable semi-flexible tails to provide stability and aid in climbing. Use of a tail counteracts the tendency of the robot to climb up an obstacle and roll over backwards, allowing even higher barriers to be cleared. With the newest V.3 Wheel-leg design discussed in Section 4, some of this tendency has been reduced, making tails less important.

Mini-Whegs™ robots (except MW-2) use two 3V CR2 lithium batteries connected in series for all power needs. These cells were chosen because of their high power density relative to their size and weight, for their flat power curves, and for their capacity to deliver very high current on demand. The 3V Lithium 1/3 N cells tested in MW-2 simply are not capable of delivering adequate power to run the robot.

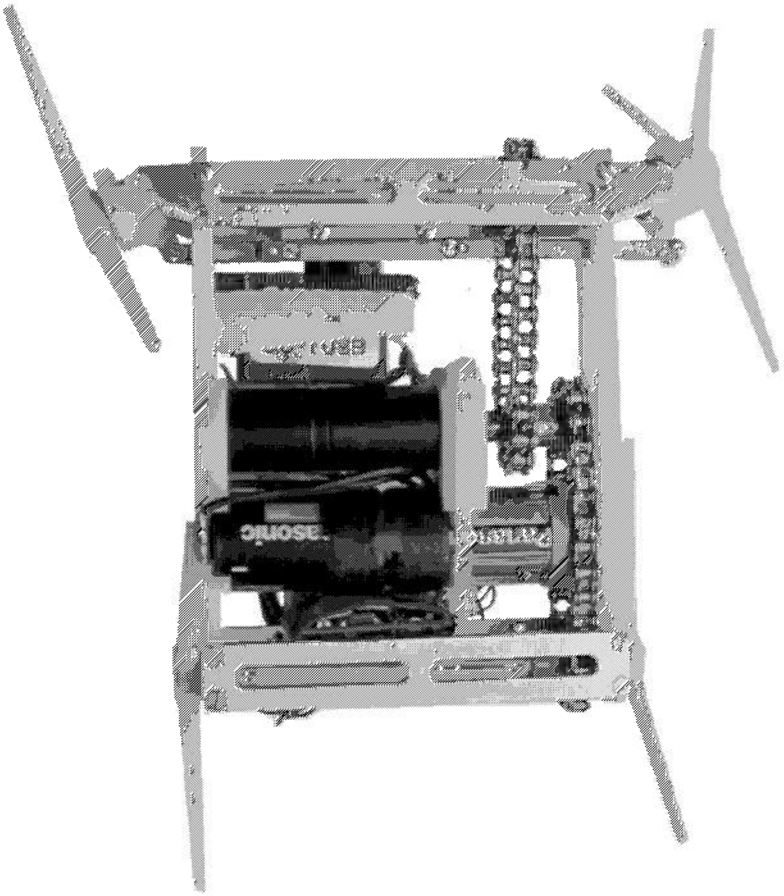


Figure 2-8. Underside close-up view of Mini-Whegs™ 3 showing component layout.

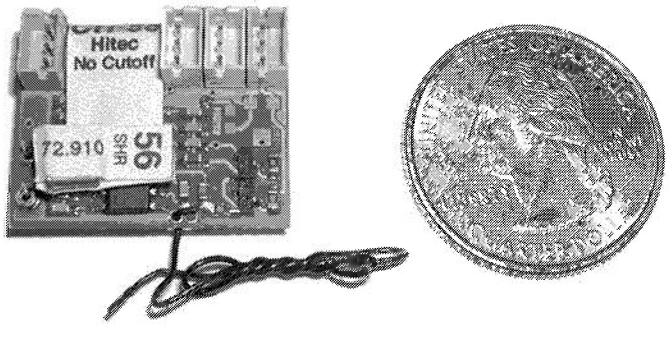


Figure 2-9. Sky Hooks and Rigging RX72-HYB sub-micro RC receiver and speed controller combination.

2.3 Mini-Whegs™ Performance and Weaknesses

The Mini-Whegs™ concept has been successfully proven with the initial prototypes, which combined impressive mobility, versatility, and speed. The primary advantage of Whegs™ wheel-legs over wheels is increased mobility on uneven terrains. Because of the three-spoke geometry, a Mini-Whegs™ robot can climb over obstacles at least 1.5 times as tall as the radius of the wheel-leg. Tests have shown that an obstacle of less than one radius high easily stops the same robot fitted with wheels of the same size instead of wheel-legs. The primary advantage of wheel-legs over legs is simplicity and high-speed operation. These 3" (9cm) long robots can run at sustained speeds of over 10 body lengths per second. In addition, because of the "high swinging" path taken by the wheel-legs, the robots are able to overcome higher obstacles than other legged robots of this scale, such as Sprawlita [5].

Weaknesses in design and performance of MW-1, 2, and 3 are expected, due to the experimental nature of the robots. Most significant of these was the torsional compliance / flexible coupling components. These mechanisms did allow a limited amount of torsional compliance between the axle and wheel-leg, but at this small scale the coupling was subject to rapid wear and failure under the high loads experienced during climbing. Other weaknesses include the unusual somersaulting behavior caused by the sharp-tipped wheel-leg foot and the tendency of the robots to high center or flip over when encountering a large obstacle. Also, like most ground vehicles with single modes of locomotion, there is no ability to climb obstacles of significantly greater scale than the length of the legs (radius of the wheel-leg). These issues and others are addressed in subsequent robots and corresponding sections of this volume.

Though the Mini-Whegs™ robots have proven capable of operating over variable terrain on the scale of the robots, they need another mode of locomotion for larger everyday obstacles such as stairs. Therefore, we undertook an effort to add jumping ability to the Mini-Whegs™ platform to enable the robot to clear obstacles several times its own body length. A variety of promising jump mechanism alternatives were devised, as described in Section 3. A viable mechanism was chosen and successfully integrated in a Mini-Whegs™ platform (Section 4). For simplicity's sake, this robot, MW-4J, lacked control and steering features found on previous robots in the series, but proved that running and significant jump ability (9" or 2.5 body lengths) could be achieved. Mini-Whegs™ 5, developed during the summer of 2002, was designed to raise overall performance levels with new bi-directional remote control, more capable Whegs™, and an enhanced steering system (Section 5).

3. JUMPING MECHANISM DEVELOPMENT

3.1 Jumping Robot Motivation – Benchmarking

Vehicle designers continuously strive to improve mobility in order to accomplish difficult tasks. Small, mobile robots can be used to carry out missions in environments too hostile for humans, in confined spaces, and in covert operations. At this scale, however, it is difficult for robots to travel long distances in a short amount of time or overcome even small obstacles.

The innovative design of Mini-Whegs™ combines the simple rotational motion of wheels with the obstacle climbing ability of legs. This proven combination provides far greater mobility than that of ordinary wheeled robots [15, 16]. Even so, the compact size of the robots prevents movement over many commonly encountered obstacles of greater relative size. Insects also face relatively large obstacles, in which case many use other modes of locomotion, such as flying or jumping.

Jumping capability would significantly augment the already effective locomotion of Mini-Whegs™. The specific goal of the portion of the project covered by this section was to prove that jumping ability could be added to the Mini-Whegs™ platform to ultimately allow the robot to clear obstacles that are several times as tall as its own body length.

The University of Minnesota's "Scout" robot (Figure 3-1) is conceptually most similar to the proposed "Jumping Mini-Whegs™" robot [6]. Though different in structure, Scout is small, simple and mobile, and is designed with primary and secondary modes of locomotion. This cylindrical robot is 4.3 inches (11cm) wide and 1.6 inches (4cm) in diameter with slightly larger wheels on each end. It is outfitted with a small, triangular spring steel mechanism used for jumping over objects up to 8 inches (20 cm) high. Because the Scout is so low to the ground, the added jumping capability has greatly increased its mobility over small obstacles.

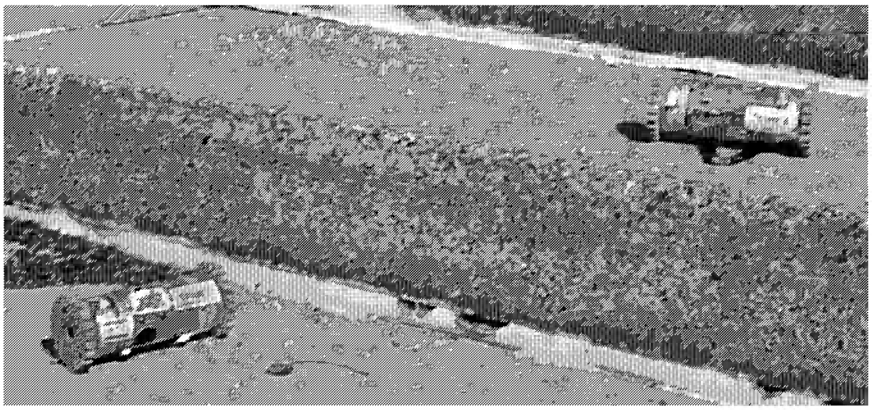


Figure 3-1. U. Minn. "Scout" robot with rolling and jumping abilities.

[Adapted from University of Minnesota website]

A jumping robot called "Hopper" (Figure 3-2) has been developed at Sandia National Laboratory's Intelligent Systems and Robotics Center (ISRC) [17]. The Sandia hopping robot is contained inside a grapefruit-sized plastic shell, shaped so the hopper rights itself after each jump. Slightly offset weighting is rotated via an internal gimbal system to control jump direction. A single gasoline-powered piston fires and strikes the ground for each jump. Even though jumping is its only mode of mobility, Hopper overcome much larger obstacles than the "Scout," with an average cycle time of 5 seconds. Jump heights of 3 feet have been achieved, with the latest versions of the robot jumping an extreme 20 or more feet.

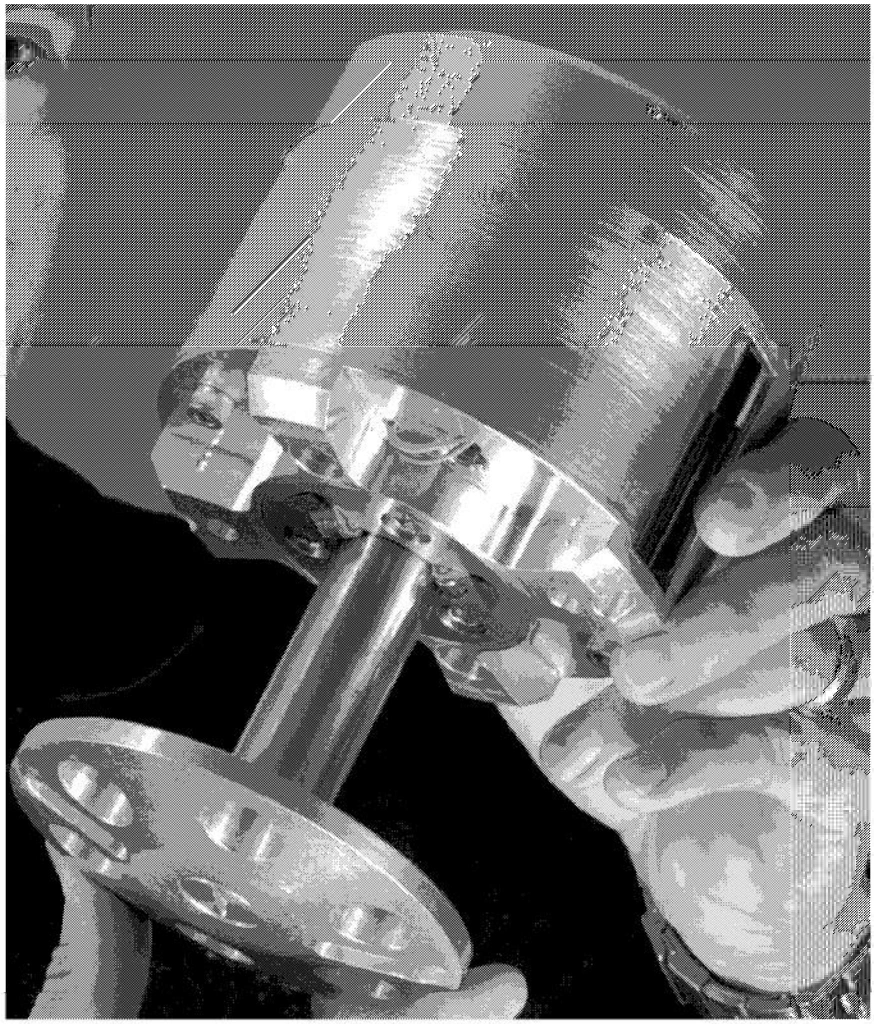


Figure 3-2. The gasoline-powered "Hopper" robot.

[Adapted from Sandia National Laboratories website]

Several other recent projects involve robotic jumping capability. For example, California Institute of Technology's “Frogbot” [3]. This 3-pound robot uses a single “leg” like the Sandia Hopper, but instead of chemical energy, it uses an electric motor and spring arrangement for jumping (Figure 3-3). The same motor is used to aim Frogbot after a hop, and the robot slowly rights itself as it stores energy for the next jump. The robot can make jumps of up to 6 feet, but requires significant time (~1 min) to reload its spring mechanism between movements.

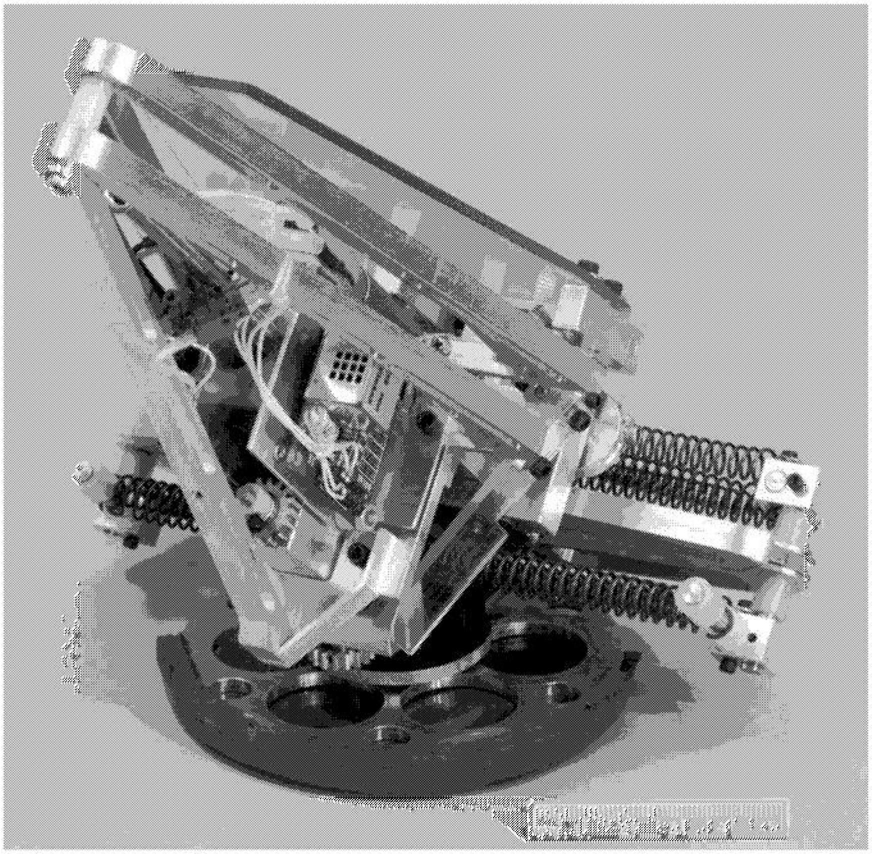


Figure 3-3. The “Frogbot” uses a single electric motor to store energy in a spring and to aim the jump.

[Adapted from NASA JPL website]

Another useful example of working jumping technology came from a highly unusual source: K-B Toys. The Gemmy Industries Corporation's “Flip'n Fido” uses an ingenious mechanical system to move and jump (Figure 3-4). Inexpensive construction and components are employed to achieve jump heights of 3 to 5 inches by this 4-inch long toy. The output from a small motor passes through a long series of gear reductions, eventually reaching a cam mechanism. As the cam slowly turns, the rear legs pivot forward, deforming a relatively stiff spring. When spring tension is released, the legs spring backward suddenly to propel the entire mechanism into a well-executed back flip. The “Flip'n Fido” product demonstrates that jumping on the scale of this project is indeed possible.

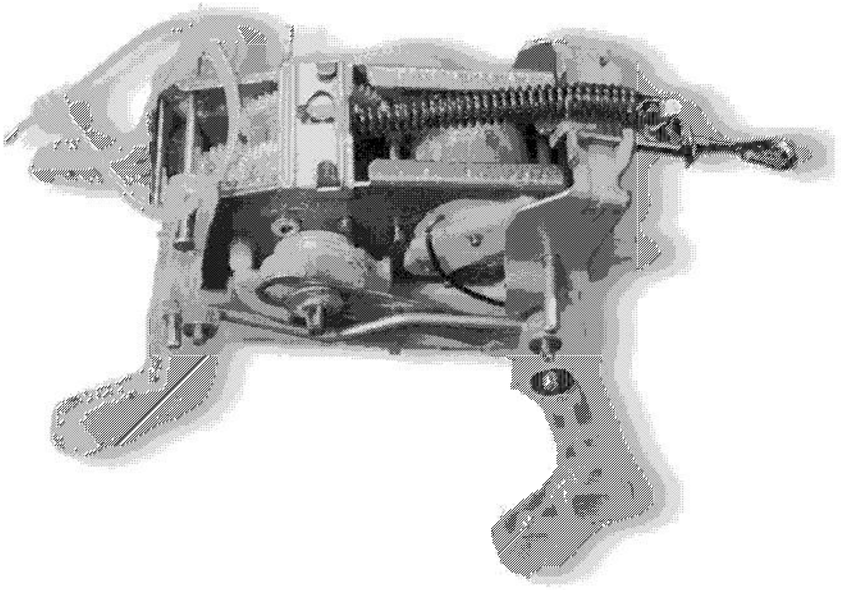


Figure 3-4. The “Flip'n Fido” toy (without exterior cover).

Interestingly, many of these jumping robot designs are wholly devoted to jumping as a means of locomotion. This project is focused toward adding jumping capability to a robot that can also run well. The primary mode of locomotion for Mini-Whegs™ is its highly effective drive system. Jumping is desired to provide a means of occasionally overcoming otherwise insurmountable obstacles.

3.2 Jump Mechanism Design Considerations

The goal of this portion of this volume was to design and test a suitable mechanism that could ultimately add jumping capability to the Mini-Whegs™ robots. The mechanism needed to rapidly release enough energy to provide a 6-8 inch (15-20cm) vertical translation. The jumping mechanism could not interfere with the current functionality of Mini-Whegs™, and both running and jumping should be powered by the existing Maxon motor/transmission combination. The desired mode for energy storage was mechanical, i.e. via elastic spring deformation. Realistic design concepts for robot integration had to be considered in determining viability of different jump mechanism alternatives. Section 4 discusses the later design and integration of the complete robot: Mini-Whegs™ 4 Jumping (sometimes referred to as Jumping Mini-Whegs™).

Key considerations for design stem primarily from the small size of Mini-Whegs™. Conceptually speaking, the small, light, and robust platform is a good candidate for the addition of jumping capability. However, the confined chassis space and the limited power and torque capability of the miniaturize components were challenges for the initial design.

The energy necessary to lift a Mini-Whegs™ robot to a height of 8 inches is approximately 0.26 J. This quantity represents the potential energy necessary for such a vertical translation, assuming all energy is transferred to motion and not lost to any other mechanism such as heat, friction or vibration. The released mechanism must provide at least this much energy after losses. Any surplus energy will result in greater mobility.

An effective jump is created by a rapid application of force to the ground. Taking into account that a small amount of the motor power ultimately is transformed into motion, the 1.2 W (J/S) rated Maxon motor used in Mini-Whegs™ would need to run on the order of several seconds to achieve the desired height - far too long for the motor to directly actuate the jump. This necessitates an intermediate method of energy storage, such as a spring, which can then release and deliver the energy more quickly.

At some point between the motor and application of force to the ground, a mechanical gear reduction is necessary. This is because many revolutions of the motor are necessary to store the amount of energy needed for the jump, but the jump occurs in a single motion. This gear change could be accomplished in a variety of ways. Initial concepts primarily fall into two categories, with a transmission positioned either before or after the mode of energy storage, requiring a different spring rate and deformation amount in each case.

For example, it would be possible to use a significant gear reduction to slowly wind a stiff spring over a small amount of deformation. This spring could then be attached to some sort of lever or foot to directly propel the vehicle when released. Alternatively, a soft spring with much greater travel could be deformed using less gear reduction. This type of spring would then release its energy over a much greater distance (or angle, etc). Since the motion of jumping requires short travel, rapid motion, and large force, the soft spring's energy release would have to be geared up. In other words, the spring would return to its initial position via a long travel, while the spring would move only a short distance when the mechanism was in contact with the ground.

The first method of direct energy release (gear reduction prior to energy storage) is more desirable for several reasons. In all gear trains, energy losses due to friction will occur. The most effective design would have the least loss between the wound spring and the jump mechanism. Also, rapid energy release is very important, and the added inertia of a transmission would reduce the acceleration of the mechanism.

Another important characteristic of the spring used in the jump system is that it be preloaded, i.e. always remain partially stretched. For the same maximum motor force available, more energy can be stored for the same amount of spring extension. At the limit (infinite preload of an infinitesimally stiff spring), twice as much energy can be stored for a given spring travel as compared to a system with no preload. This is explained by the fact that in an ideal spring, force is linear with respect to displacement while energy storage is quadratic. Let us further examine the difference between preloaded and non-preloaded systems.

The force provided by a linear spring is its spring constant or stiffness k times the displacement x from its relaxed length.

$$F = kx \quad where\ x = \text{Displacement from no load} \tag{1}$$

Thus, the spring constant and displacement can be varied inversely without changing the reaction force. The energy stored in a spring at a given displacement is given by the integral of this equation in terms of x, or the area under the force-displacement curve:

$$E_x = \frac{1}{2}Fx = \frac{kx^2}{2} \tag{2}$$

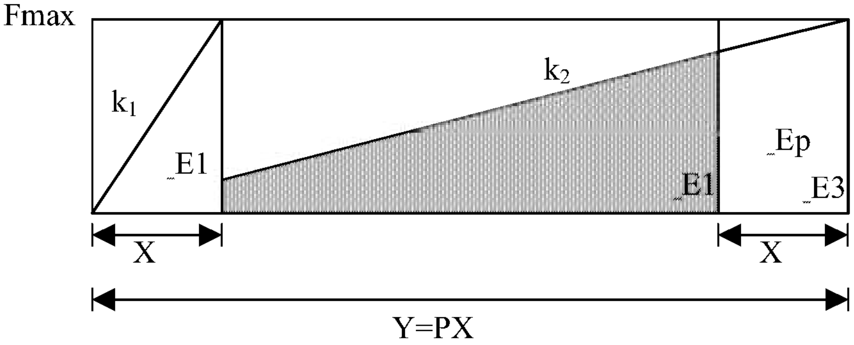


Figure 3-5. For a given displacement and maximum motor force available, using a compliant spring under preload will allow for greater energy storage, shown by the area in yellow under the force/displacement curves.

Consider the force-displacement curves of two springs of high (k_1) and low (k_2) stiffness, shown in Figure 3-5. They will both be tested on the same robot, with a maximum motor force available, F_{max}. The robot's jump mechanism also has a limited amount of travel, X available to activate a jump mechanism. In the first case, the k_1 spring is wound from an unloaded position. In the second case, the k_2 spring is preloaded to position 2 and is then wound the same distance, X, to position 3. In this case, the amount of preload, P, is calibrated such that the end of the useful travel also corresponds to Fmax. The preload, P, in the second case can be characterized as the ratio of the entire displacement to the useful displacement, thus a preload of one is equivalent to starting from an unloaded position. Let's compare the energy stored by the two configurations.

Define a pre-stretch parameter, P

$$P = \frac{Y}{X} \quad where \quad \begin{array}{l} \text{Y = Total Displacement} \\ \text{X = Used Displacement} \end{array} \tag{3}$$

where P≥1.0. The maximum forces are given by

$$F_{\max} = k_1 X = k_2 Y = k_2 P X \tag{4}$$

from which the relationship can be determined

$$k_1 = k_2 P \tag{5}$$

The energy, E_1, stored in the first configuration (no preload) is

$$E_1 = \frac{1}{2} F_{\max} X = \frac{1}{2} k_1 X^2 = \frac{1}{2} P k_2 X^2 \tag{6}$$

The useful energy stored in the preloaded spring (E_p) is equal to the energy stored at maximum displacement (E_3) minus the energy stored at the preloaded position (E_2).

$$E_p = E_3 - E_2 = \frac{1}{2} k_2 Y^2 - \frac{1}{2} k_2 (Y - X)^2 = \frac{1}{2} k_2 X^2 (2P - 1) \tag{7}$$

To compare the amounts of useful energy stored in each scenario, we construct the ratio,

$$R = \frac{\text{energy stored in preloaded system}}{\text{energy stored in non preloaded system}} \tag{8}$$

Substituting and simplifying, yields the following:

$$R = \frac{E_p}{E_1} = \frac{2P - 1}{P} \quad and \quad \lim_{P \to \infty} R = 2 \tag{9}$$

Thus, the maximum theoretical energy storage (using infinite preload) is twice what is possible without preload, given a maximum motor torque and available mechanism travel. A more realistic example is the case where P = 2, i.e. the preloaded position is half of the maximum extension of the spring. In this case, R would be equal to 3/2, in other words a 50% increase in stored energy using the same motor, simply by using a softer spring with a small amount of preload. This ratio proves that any amount of preload is beneficial under the conditions and assumptions previously mentioned. The same results can also be determined graphically from Figure 3-5.

3.3 Jump Mechanism Design Concepts

With the above design considerations in mind, many different mechanisms using torsion, linear, and flat (bending/buckling) springs were considered. The range of viable jump mechanism designs was narrowed based on several key considerations, including simplicity and expected performance. Based on these and other considerations, three designs were chosen and tested on a statically and dynamically analogous model of the robot. Working Model software was also utilized for 2-D model simulation to gain a sense of different mechanism dynamics.

The first chosen design was inspired by certain operational characteristics of the Mini-Whegs™ 3 robot. The robot has a very compact size and shape and extremely high available torque and traction. If full power is applied from a standstill with the initial sharp-tipped wheel-leg design, it is possible for the robot to actually flip over and reverse direction (Section 2). Because the design is symmetrical, it functions when upside down. Additionally, when the robot encounters an obstacle, there is often enough traction such that it is able to drive partway up a vertical obstacle and flip over. To keep the robot right side up, a small spring steel tail was added to early Mini-Whegs™ designs.

This tail inspired the design of the "Scorpion" jumping mechanism (see Figure 3-6). A 0.010" thick spring steel sheet extends back from the underside of the robot. To store energy, the steel is bent forward over the top of the robot, somewhat resembling the defensive posture of a scorpion. For jumping over an obstacle, the robot must flip over onto the tensed steel, which is then released (see Figure 3-7). Steel thickness and tail configuration can be varied to achieve desired results. Winding concepts using a small cable winch were outlined.

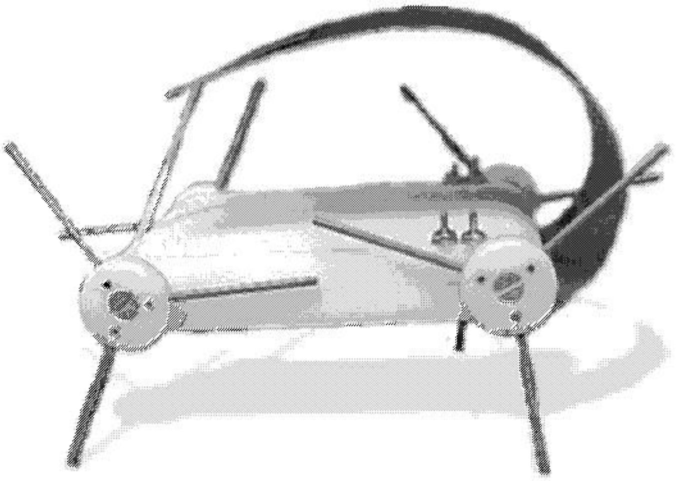


Figure 3-6. The "Scorpion" Design Concept – Cocked.

The second design chosen for testing was dubbed the "Mousetrap" (see Figure 3-8). This stemmed from an initial experiment where it was discovered that a mousetrap spring has more than enough energy storage capability to perform the desired jumping motion. Torsional springs are attached to the bottom of the robot and preloaded for the reasons previously discussed. The springs attach to a lever arm, which in turn contacts the ground with a downward rotating motion. Energy is stored and released over 180 degrees of travel. This distance could easily be limited by a physical stop to the first 90 degrees for quicker winding, as the robot is no longer in contact with the ground after that point. Key variables included length of the lever arm, location of pivot point, and strength and preload of the spring.

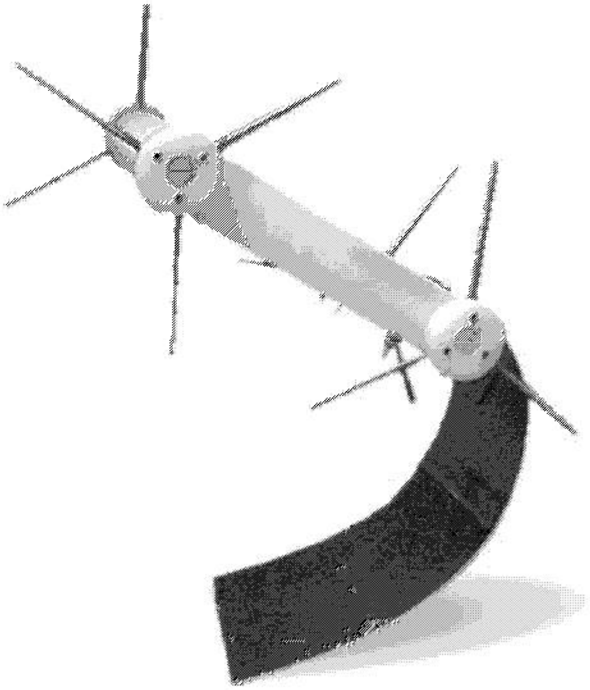


Figure 3-7. The "Scorpion" Design Concept – Released.

The "Flying Four-Bar" concept is, in some sense, a progression of the Mousetrap design, with modifications to increase jump stability. It uses a centrally placed linear tension spring and parallel four-bar mechanisms attached to the sides of the robot. The four-bar mechanisms pivot at two points on the body of the robot, and are constrained to each other via an axle and two cross-bars. These low profile parallel "legs" fold up compactly on each side of the body inside the wheel-legs until released. In order for the lower links of the four-bars, or "feet," to contact the ground directly under the center of the robot, the connecting joints are placed at the extreme rear of the robot. The legs are designed to be as long as possible to provide a gradually changing line of action of ground contact force as the legs follow their trajectory. This kinematic arrangement is designed to provide a consistent jump trajectory of forward and up, while imparting minimum unnecessary rotational motion to the robot. Initial designs aligned the foot to be parallel with the ground to obtain maximum stability, while later iterations explored an inclined orientation (see Figure 3-9).

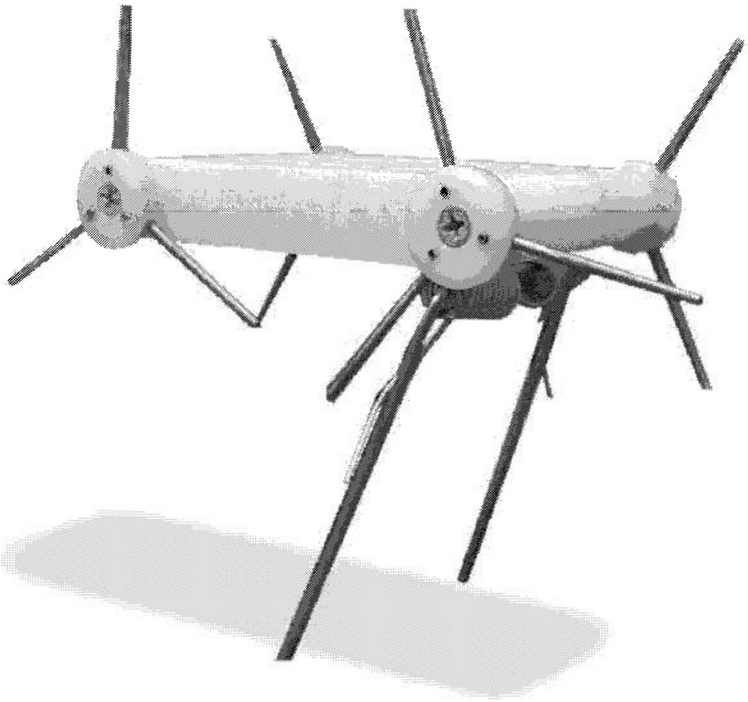


Figure 3-8. The "Mousetrap" Concept.

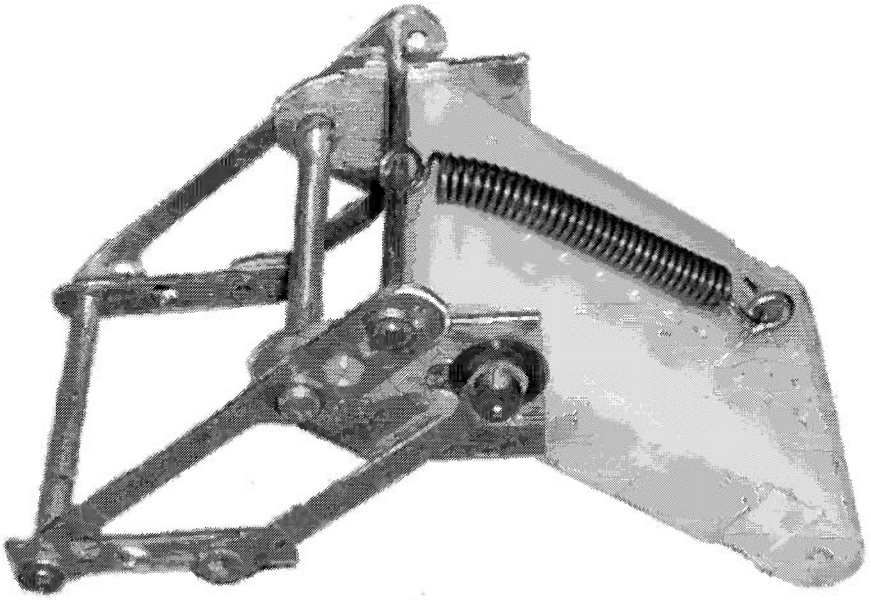


Figure 3-9. The "Flying Four-Bar" Concept.

3.4 Design Alternative Testing and Results

During the design phase, jumping robot prototypes were simulated, built, empirically tested, and modified. Working Model software was utilized for 2-D model simulation of kinematic mechanisms. The Mousetrap, and, later, the Flying Four-Bar concepts were modeled using this software to confirm expected behavior. The effects of varying the spring constants and lever arm lengths of the design were also simulated. These simulations saved prototyping time, and were later confirmed by visual observations of the stability and performance of the designs. For time-efficiency, the Scorpion design was prototyped directly due to the complexity of simulating large magnitude beam deformations.

Preliminary designs were constructed using Delrin wheel-leg mock-ups of similar size, weight, and inertia. During testing, improvements were made and the prototypes were re-tested until the desired performance was achieved. Finding the correct placement of the jumping mechanism in relation to the robot's center of mass was an example of a result of testing. The jump mechanism concepts were loaded manually. Care was taken to apply reasonable amounts of force, on the same order of magnitude as the capabilities of the Maxon motor. Performance differences were naturally expected with the evolution of the concepts, and ultimately when using the motor for winding the spring.

To prove that the capabilities of the motor were not being exceeded, an experiment was conducted in which the winding force was characterized for the "Scorpion" Mini-Whegs™ jumping design. Results from this experiment proved that the current Maxon motor/transmission combination in Mini-Whegs™ could provide enough torque to retract the proposed spring steel geometry.

The results from the empirical testing of the simple Scorpion design were very encouraging. Average jump heights of 22" were achieved using 0.010" thick spring steel for the Scorpion design as discussed above. Average jump heights of over 4' were achieved with 0.015" spring steel, though the force necessary for energy storage with this thickness spring is not practical for the motor/transmission combination in use. Overall, the jumps were stable and consistent, with minimal rotation, due to the very large ground contact area of the spring steel and steady release of energy. Small variations in loaded spring position produced negligible differences in performance. Unfortunately, the proposed mechanism is relatively large compared to the robot, which could pose issues for integration. Also, it was obvious that some of the stored energy was lost to vibration after the mechanism struck the ground and became airborne.

The Mousetrap design proved less tolerant to variations in the design parameters. The desired jump height of 8 inches was achievable, but was subject to considerable rotation, indicating that significant energy was being wasted to create undesirable motion. This flipping was due to the small contact area of the jump foot, and the rapidly rotating motion of the jump legs when released. The design imparts backward force as the robot leaves the ground so as to create significant angular momentum. Experimentation with different springs and leg lengths slightly improved performance, but inconsistency was still an issue. Positives include simplicity and the compact and low profile nature of the design when cocked.

The parallel Flying Four-Bar mechanism proved highly successful. The prototype jumped the desired 6-8 inches in a desirable and predictable - - almost frog-like - - fashion: forward and upward with little rotation of the chassis. The Flying Four-Bar design combines positive features from both previous designs. Like the Mousetrap, its compact retracting mechanism will not interfere with regular operation of the robot when cocked. The relatively large contact area of the feet and smooth downward and back trajectory of the mechanism creates consistent jumps, much like the Scorpion design. Minor issues associated with the more complicated design are the only negatives.

Experimentation with the initial four-bar design led to an interesting modification. When first constructed, the foot was aligned with the horizontal axis of the robot, essentially parallel to the floor, to provide stability and consistent behavior when jumping. During one test the front of the robot was angled upward from the horizontal by approximately 30 degrees before jumping, much like the angle of a frog's torso when preparing to jump. The results were remarkable, with jumps up to 20 inches high and up to 24 inches forward. The inclined angle caused only the small rear portion of the foot to contact the ground, but over a much longer stroke, which was more directly in line with the robot's motion. As a small tradeoff, the smaller foot contact size causes a fraction of the instability seen in the Mousetrap design. In exchange for vastly increased performance, the prototype performs at most a single back flip, which is typical for cricket jumping. As a result of this test, the jump mechanism was remounted on the body of the robot mock-up with a downward angle, to mimic the performance achieved by inclining the body of the robot.

3.5 Discussion and Conclusions

In an effort to increase the mobility of the small mobile robot, Mini-Whegs™, the design of a feasible jumping mechanism was devised. Many jumping mechanism concepts were theorized, and several proved worth further investigation. Testing of the preliminary design prototypes indicated that creation of a jumping robot of the desired size and weight was achievable. The prototypes were evaluated with emphasis on energy conversion, consistency, and jumping performance. Final selection of the jumping mechanism was based on overall mechanism performance, feasibility of system integration, and practicality of design.

The Flying Four-Bar design was selected for further development because of its many strengths, including jump height, stability, consistency, and the observed ability to convert more of the stored energy into motion. These positive characteristics outweighed the few negative marks associated with its slightly more complicated design. Additionally, the four-bar provides options for variations and future design flexibility. Motion can be imparted to the single degree of freedom mechanism by a variety of means, including a torsion or (tested) linear spring. The angle that the mechanism is mounted to the chassis can be varied, as well as the lengths of the segments of the legs or foot, to achieve different trajectories. Different spring rates and amounts of preload can easily be tested to further refine performance. The design of this mechanism is described in much greater detail in the Section 4.

Section 4 deals with design and construction of a working robot, complete with jumping mechanism. Specific goals include running and jumping powered by the same motor, and repeated, automatic jump capability. Challenges include creation of a suitable method of energy storage in the spring, method of controlling or actuating the release of the energy, and integration of these additional components into the compact Mini-Whegs™ chassis.

4. DEVELOPMENT OF A JUMPING MINI-WHEGS™ ROBOT

4.1 Introduction

In this section the design, construction, and performance of Jumping Mini-Whegs™ is described. This robot is a working prototype which successfully demonstrates that jumping ability can be added to the Mini-Whegs™ platform. Jumping heights of over 9 inches (22cm or 2.5 body lengths) have been achieved, which is greater than the height of one standard stair. The robot uses the same single drive motor and transmission used by other Mini-Whegs™ robots to simultaneously power both running and jumping modes of locomotion. Loading and actuation of the jump mechanism is fully automatic; while the robot runs, the jumping mechanism slowly retracts, releases, and then repeats.

Jumping Mini-Whegs™ is similar in design and construction to the other Mini-Whegs™ robots, with some key differences. Since steering and control were unnecessary to prove the jumping concept, related components were omitted and replaced with a simple solid front axle. The Delrin sides of the robot are similar in design and function to those of other Mini-Whegs™ robots, but they also support the additional components of the jumping mechanism. These components include a secondary 275:1 transmission and a parallel four-bar jumping mechanism attached to the frame via two axles.

Figures 4-1 and 4-2 show the overall layout of the Jumping Mini-Whegs™ vehicle. The Maxon motor/transmission combination (A) used in Mini-Whegs™ 3 is again used to drive the front (B) and rear (C) axles. The additional jump transmission (D) is powered from the rear axle via a sprocket-chain combination (E). The “slip-gear” (F), which is mounted to the output of (D), provides intermittent and repeatable operation of the improved “Flying Four-Bar” jump mechanism (G). The mechanism stores energy in a centrally located spring (H), and uses interlocking titanium legs (J) and spiked aluminum feet (K). The design and development of each of the major systems comprises the remainder of this section.

4.2 Design

In order to implement the "Flying Four-Bar" jumping mechanism concept chosen in Section 3, an automatic and repeatable energy storage method was required. Desired jump height is 8" (20cm), with a forward trajectory to help in clearing obstacles. Other goals included retaining Mini-Whegs™' features of simplicity, small size and low weight. The current onboard motor should power retraction in addition to driving the front and rear drive axles. The jumping mechanism, retraction system and new drive train components must be integrated into the current Mini-Whegs™ platform, preferably with as few major changes as possible. Challenges included limited available space, and achieving desired performance using miniature components, which provide limited amounts of torque and power.

4.2.1 Mechanism Actuation

Since the Flying Four-Bar mechanism has only a single degree of freedom, retracting the mechanism is synonymous with storing energy in the spring. To that end, multiple concepts for energy storage and release were generated. Initial designs varied widely, from electromechanical options such as servos or solenoids to cable winches to cam/rocker devices. Ultimately the mechanical "slip-gear" method was chosen. With this method, the jumping mechanism is automatically and repeatedly activated, and involves no active control input. As MW-4J is designed to be a demonstration vehicle for jumping mechanism integration, this level of control is sufficient.

The slip-gear component (Figure 4-3) consists of a small gear with several teeth removed. It interfaces with an unmodified gear of the same size that is fixed to one of the rotating crossbars in the four-bar mechanism. The drive motor turns the slip-gear continuously, which rotates the four-bar mechanism in the direction necessary to store energy in the spring. The slip-gear is calibrated so that its teeth will remain in contact with the standard gear just long enough to wind the mechanism to its retracted (loaded) position, or approximately 100 degrees of rotation. The slip-gear continues to rotate and reaches the gap where the teeth have been removed; at which point the motion of the mechanism becomes unconstrained. The large spring force causes it to suddenly release to its open (unloaded) position, creating a jump. As the slip-gear continues to rotate, its teeth re-engage and the winding process is repeated.

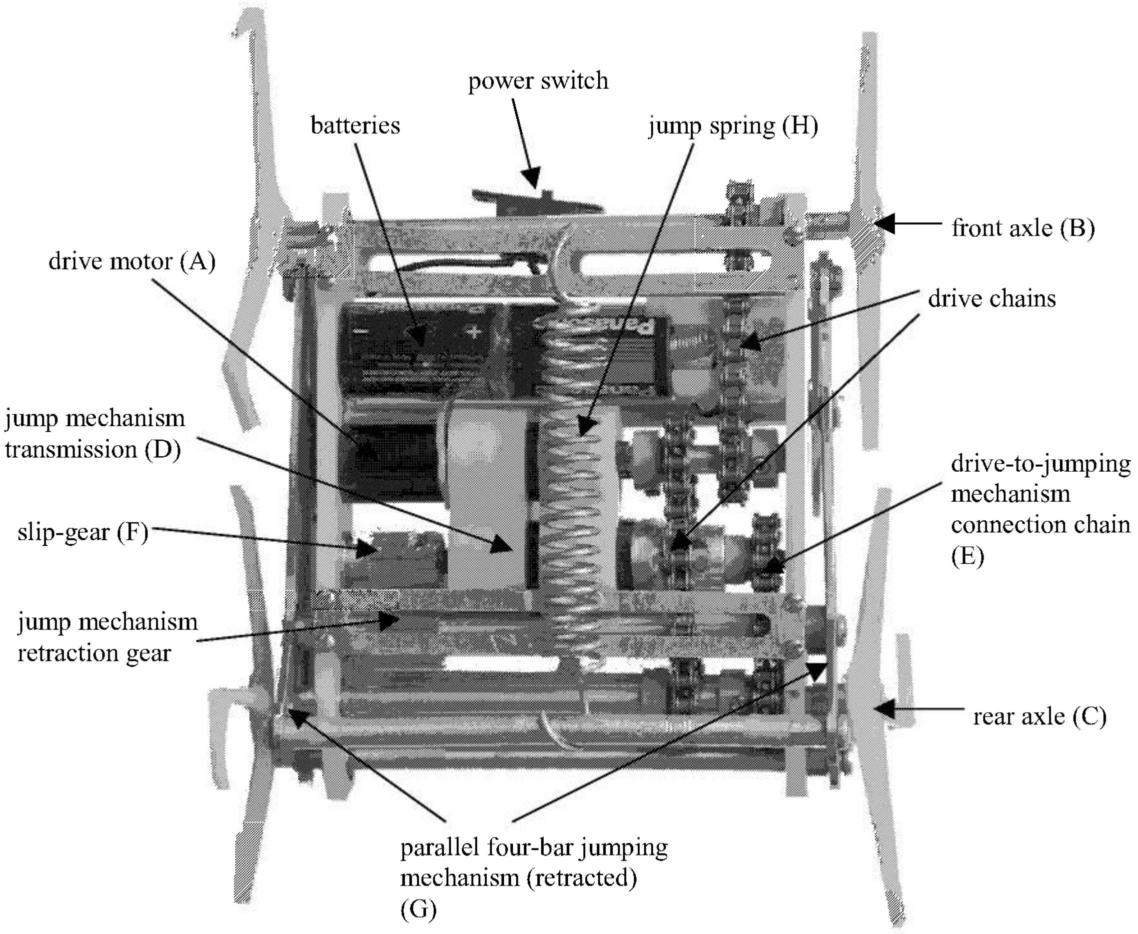


Figure 4-1. Top view of complete Jumping Mini-Whegs™ robot.

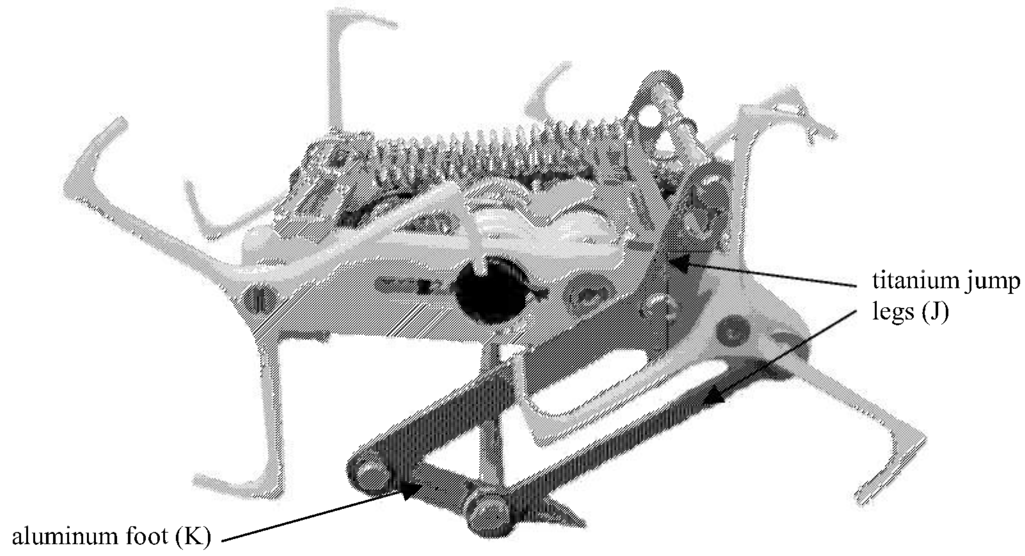


Figure 4-2. **Side view of complete Jumping Mini-Whegs™ robot with partially retracted jumping mechanism.**

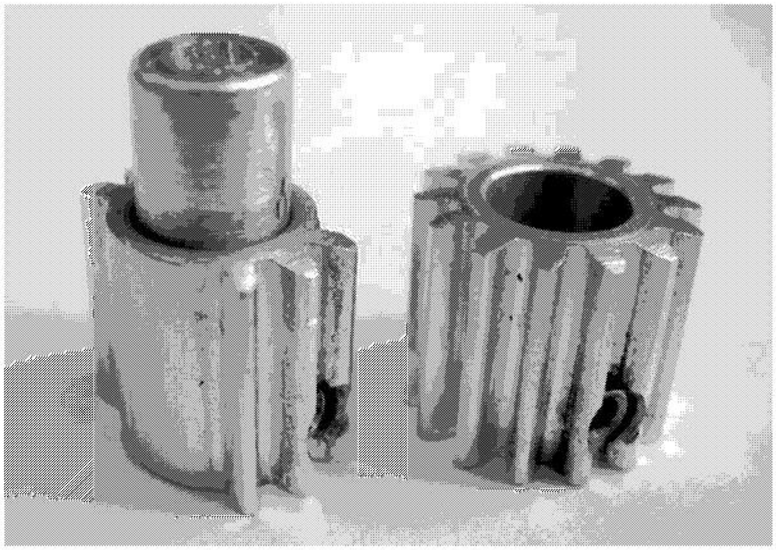


Figure 4-3. **Close-up photo of 0.5" slip-gear (left) and its mate, which provide automatic and repeating jump mechanism actuation.**

In order for the relatively stiff spring to be deformed by the Maxon 1.2 W motor and 67:1 transmission of the robot, an additional gear reduction is necessary, as discussed in Section 3. This function is accomplished by a secondary Maxon 275:1 planetary transmission, for a combined gear reduction for the jumping mechanism of 18,545:1. The slip-gear is directly mounted on the output shaft of this transmission. The input shaft of the transmission is connected to the rear drive axle of the robot via sprockets and chain. The remainder of the drive train is the same as in a standard Mini-Whegs™ robot, i.e. the motor drives the front and rear axles, and attached Whegs™, via two sets of chain-sprocket pairs.

Integration of the secondary Maxon 275:1 transmission posed some difficulties. Maxon transmissions are delivered attached to motors and are generally not available as separate components. This is because the motor and transmission housings interface directly in order to provide an extremely solid connection and high precision alignment. Thus, the output shaft of the motor serves as the input shaft to the transmission. Fortunately, representatives at Maxon were able to provide the desired transmission, but they expressed concern due to the fact that a very precise custom input shaft would need to be designed and manufactured.

Requirements for the transmission input system included providing a suitable mount for an extremely small input pinion (0.065"), or sun gear, for power input to the planetary transmission. All relative radial and axial motion between the transmission and the new shaft had to be eliminated to ensure excessive loads were not placed on tiny internal transmission components. The input shaft also had to support a sprocket/chain connection to the existing drive system of the robot.

A two-part shaft and housing system was devised to meet these requirements (see Figures 4-4 and 4-5). Several precision micro-bearings were placed between the steel shaft and aluminum housing, which serve to support and isolate the shaft. Axial motion is restricted by placing a larger diameter shaft segment between bearings that are constrained by the housing. The aluminum housing is machined with fine metric (12.2 x 0.5mm) threads on its exterior, which interface with threads on the interior of the transmission casing. The shaft proved exceptionally challenging to machine, as the diameter tolerance necessary to press-fit the 0.039" (1mm) pinion hub were on the order of 0.00025 inches.

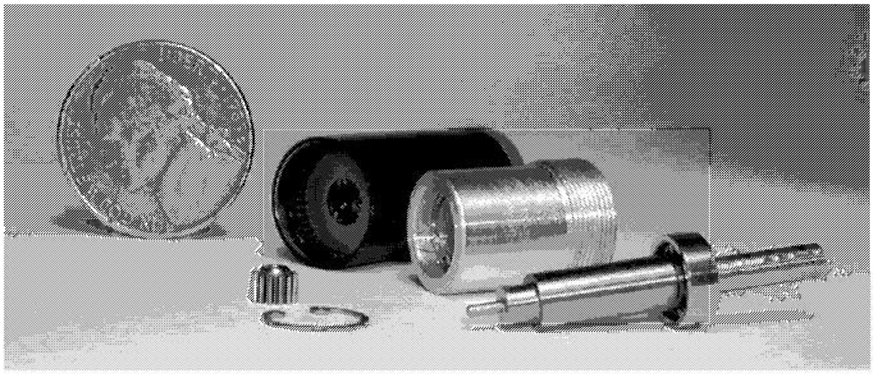


Figure 4-4. The use of a secondary 13mm Maxon 275:1 transmission necessitated custom miniature components including input shaft and housing. The 0.065" pinion and 0.015" thick retainer ring can be seen.

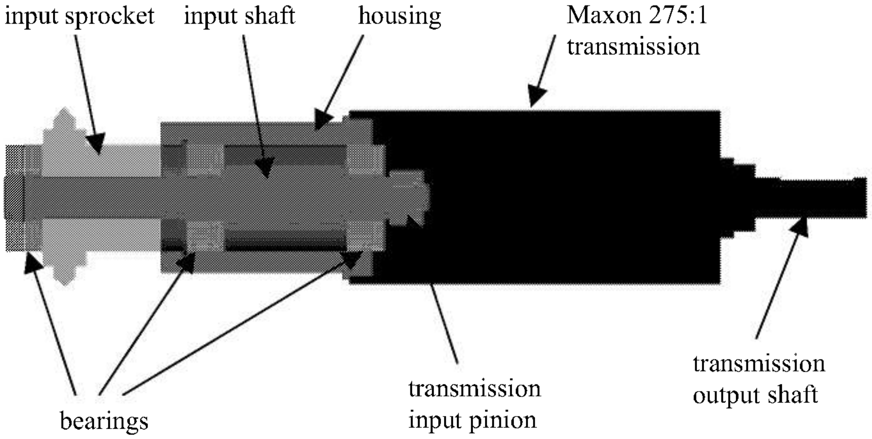


Figure 4-5. Section diagram of transmission and miniature components including input shaft and housing.

4.2.2 Four-Bar Development

In Section 3.3, the selection of the parallel Flying Four-Bar jumping mechanism is discussed. It was chosen for the desirable trajectory it provided, the compact design, and the ability to vary key performance parameters. Analysis has shown that a relatively soft spring with significant preload provides the maximum energy storage. For more rapid implementation, a suitable jump spring was chosen by experimentation with these principles in mind. A number of additional modifications to the original Flying Four-Bar design were necessary for implementation on Jumping Mini-Whegs™.

After use, the slender aluminum legs in the Flying Four-Bar mockup (Section 3.4) experienced deformation. Spatial constraints, including limited clearance between the body of the robot and the Whegs™, did not allow the legs to be strengthened by the addition of material. Therefore, a stronger material was necessary. Titanium was chosen because of its combination of high strength/weight and toughness. Aluminum is of sufficient strength for the feet and cross bars.

The version of the Flying Four-Bar used in Jumping Mini-Whegs™ is designed to be as rigid and strong as possible (see Figure 4-6). To constrain and synchronize motion between the two sides, cross-braces are used at three of the four pivot locations. An additional cross brace connects extensions of the front jump legs, and serves as the attachment point for the spring. The cross braces at the two upper pivot points double as axles, and rotate in ABEC-5 precision micro bearings. The larger drive axle has flats on its connection with the legs to create a torsionally strong connection with each side and to transfer moment to the jump legs.

The kinematic design of the jumping mechanism was calibrated to provide a desirable jump trajectory, as discussed in Section 3. The body-based (upper) pivots were placed as far rearward as possible. The legs were designed to be as long as possible (2.8”), without contacting the front drive axles. Spacing between the legs (0.8”) and foot length were adjusted such that the contact point of the mechanism was below the center of mass of the robot. The body-based upper pivots of the mechanism were aligned with a 20-degree downward angle for increased performance (Section 3).

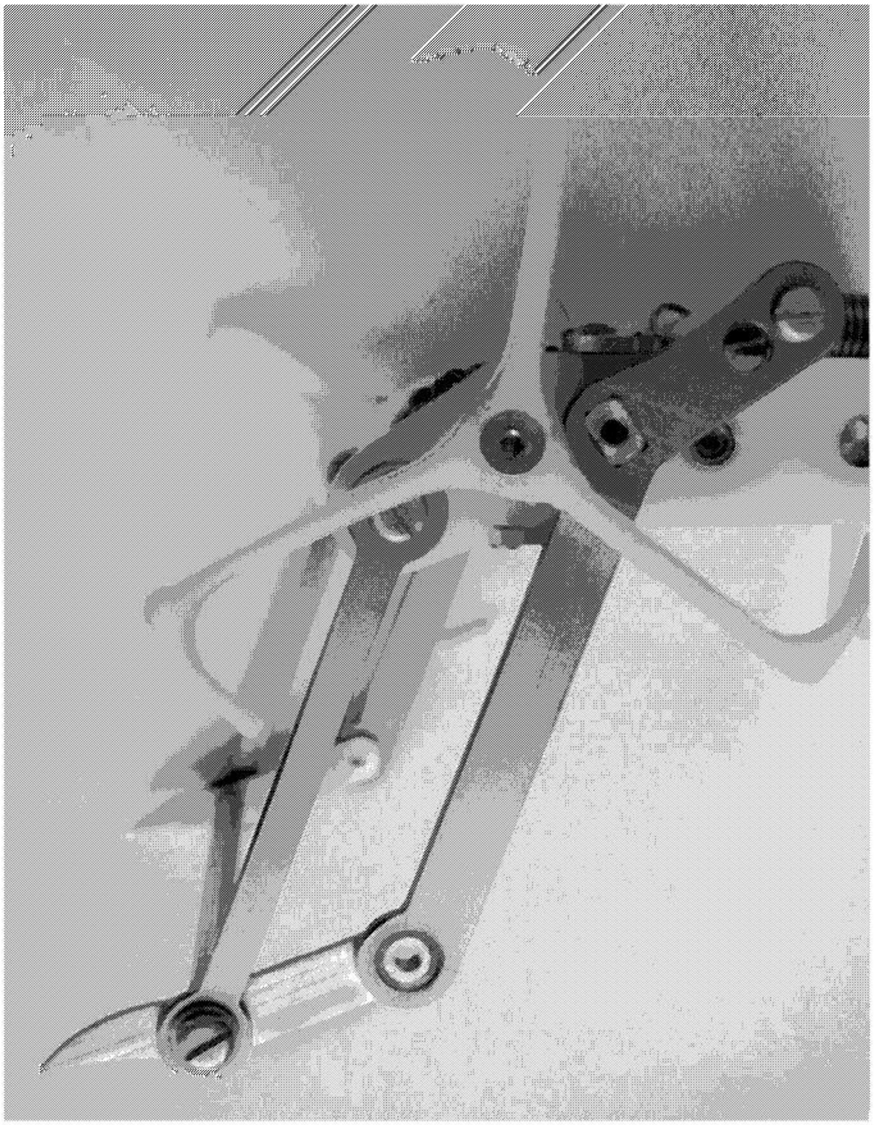


Figure 4-6. Improved Flying Four-Bar mechanism implemented on Mini-Whegs™-4J. Flats on the drive axle transmit power and synchronize the motion of the two sides. Some assembly screws have been removed to show detail.

As the jumping function only operates intermittently, it must not interfere with the regular locomotion of the robot. In order for Jumping Mini-Whegs™ to run unhindered and retain the obstacle clearing ability of Mini-Whegs™ 3, the jump mechanism must be capable of being retracted against the chassis of the robot. The legs are designed so that they interlock when folded to take up a minimum amount of space. A cross bar cannot be used to stabilize the forward foot pivot because those pivots occupy the small space between the frame and front wheel-legs when the jump mechanism is retracted. The lower rear pivots are connected by a cross member to strengthen the mechanism, reducing the ground clearance of the robot by a small amount when the mechanism is retracted.

The relative locations of force inputs and outputs in the single degree of freedom four-bar system implemented on MW-4J are important. These include the spring attachment, ground contact point, and the mechanism drive gear, which mounts to an upper pivot axle and interfaces with the slip gear. Ground contact occurs at the lower rear pivot point, but the gear and spring attachment locations can be varied. In the Flying Four-Bar prototype (see Figure 4-7), the system was loaded by hand, so the drive gear was not a consideration. The spring was attached to a crossbar between extensions of the rear legs (e). Thus, when the mechanism was triggered, the force of the spring is transmitted directly through the back legs to contact the ground (f). In this manner, excessive loading of the un-reinforced lower front pivot points (a) is avoided.

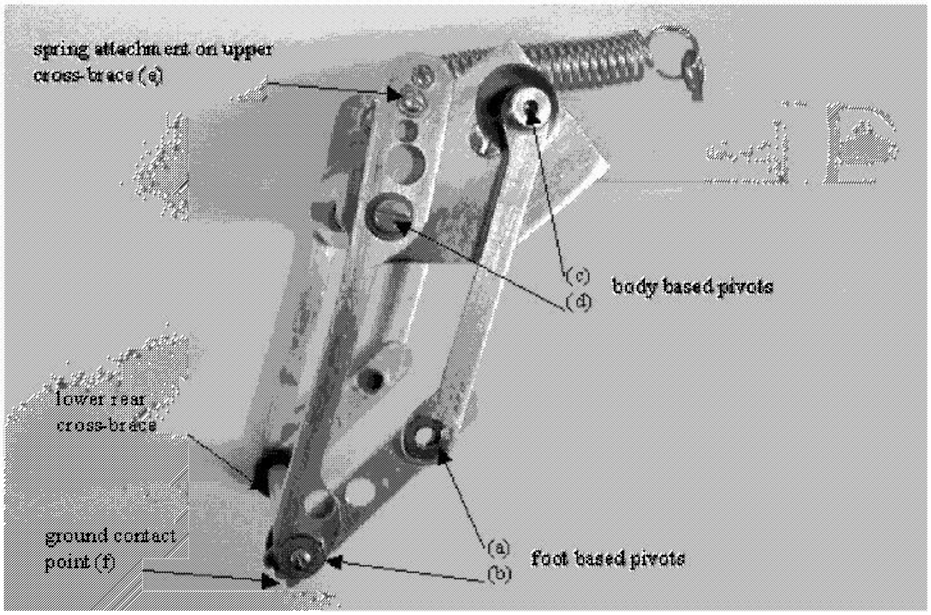


Figure 4-7. Original Flying Four-Bar jumping mechanism prototype.

With integration of the Flying Four-Bar concept into MW-4J (see Figure 4-8), placement of the gear for winding the mechanism created a challenge. Ideally, the rear legs would be used as the location for both the gear and spring attachment, such that the other pivots (A, C) of the system remained relatively unloaded throughout both loading and release cycles of the system. Unfortunately, after much design work, space considerations dictated that the gear be mounted to the front jump axle (C). This is due to the fact that the gear must interface directly with the slip-gear, which is attached to the 275:1 jump transmission. These components could not fit within the frame in such a manner as to drive the rear jump axle. By moving the drive gear to the forward jump axle, the force of winding would have to be transmitted all the way through the mechanism, leading to larger stresses on the weak points of the design, the lower front pivots (A). If the spring attachments were also moved to the front legs (E), the force of winding would be transmitted directly from the gear to the spring. However, the force of jumping would have to be transmitted from the front legs through the lower front pivots to the ground (F).

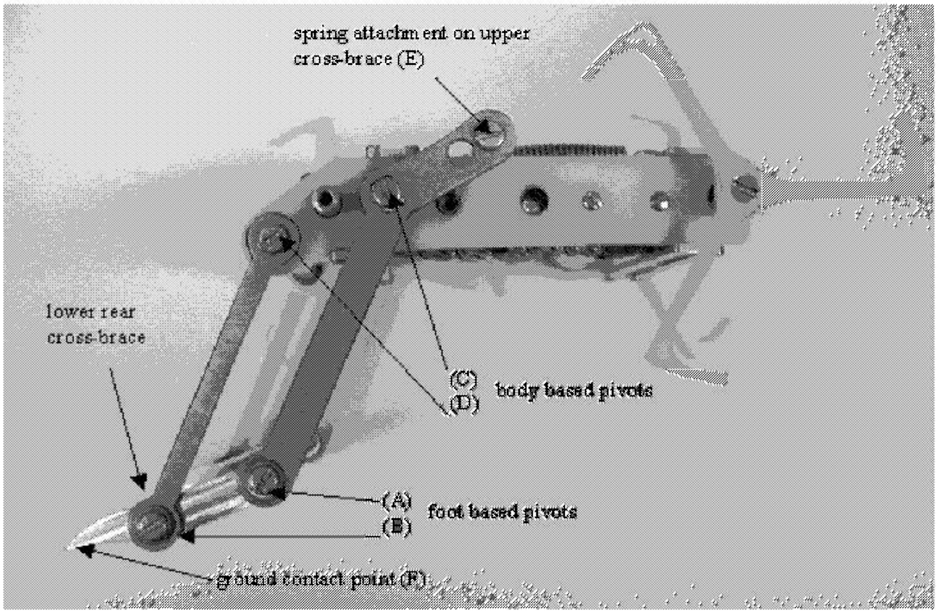


Figure 4-8. Improved four-bar jumping mechanism used on Jumping Mini-Whegs™

One advantage of this layout is that it makes the robot significantly more compact when the jump mechanism is fully retracted. By attaching the spring to extensions of the front legs instead of the rear, components of the jump mechanism do not extend behind the robot, unlike with the rear-mounted spring in the Flying Four-Bar design. The decision was made to strengthen the pivot points and both load and unload the jump mechanism via the front axle.

The lower front pivot connections proved to be a challenging aspect to the mechanism design. They needed to have a low profile cross-section less than 0.220 inches (5.6 cm) each, while being strong enough to transmit the force of the jump. The corresponding front lower pivots of the Flying Four-Bar served only to constrain the motion of the foot, rather than deliver significant force because the spring in that design was instead connected to the rear legs. The pivots were merely required to hold the foot and front leg together, and consisted of a simple snap bearing. To improve pivot strength in Jumping Mini-Whegs™, the aluminum foot segments of the four-bar mechanism were machined with two protruding round bosses, which fit into holes in the titanium legs (see Figure 4-9). The legs rotate relative to the foot on a thin brass sleeve bearing around the boss. A 0.005” thick Teflon washer was added between the boss and leg to reduce friction. A washer and short screw, which is threaded into the boss, hold the components together.

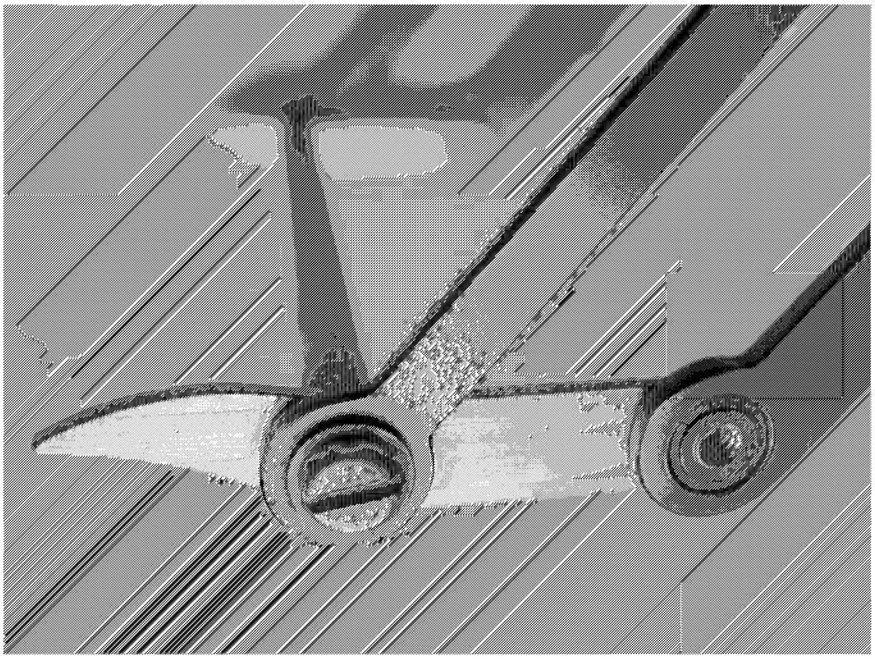


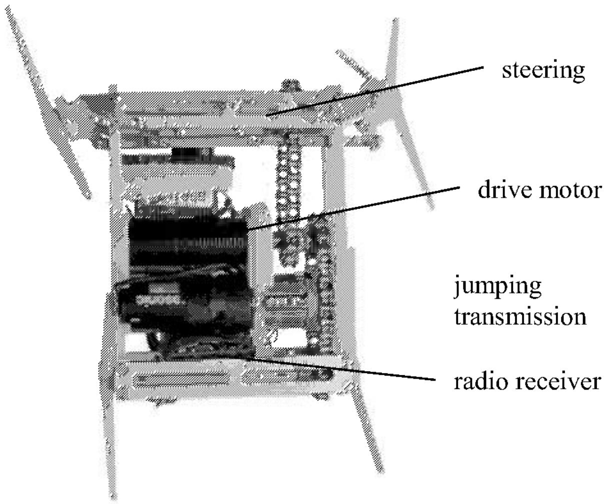
Figure 4-9. Modified foot design (with heel spike) and lower pivot detail of double four-bar jump mechanism.

4.2.3 Chassis Redesign

The chassis layout of Mini-Whegs™ 3 was used as a starting point for the design of the Jumping Mini-Whegs™ chassis (see Figures 4-10 and 4-11). To accommodate a variety of new jumping mechanism components, significant drive train and component spacing modifications were necessary. Overall methodology focused on making the robot body as compact as possible by first determining constraints and inflexible distances, and placing remaining components as closely possible. Certain components were constrained by factors such as gear pitch diameters or sprocket and chain clearances. Analysis was performed to determine minimum possible length and width of the robot. Spacing between chain driven axles is limited to finite increments and was carefully determined to ensure proper chain tension without the use of additional tensioners. The final chassis dimensions of the frame are 3.7” long x 3.0” wide, compared to 3.3” x 2.5” for Mini-Whegs™ 3.

4.2.4 Manufacturing

The majority of robot components were machined using 3-axis Roland CNC (Computer Numerical Control) machines. These components included the frame sides and cross-braces, the jump legs and feet, the wheel-legs, and a variety of smaller components. Manufacturing parts by this method involves creating the parts in Pro/ENGINEER design software and outputting suitable code for the CNC machine to determine a variety of cutting parameters. A correctly sized hand-machined material "blank" is then fixed in the CNC machine. After an alignment procedure and tool selection, the machine automatically makes the desired cuts into the material by moving a drill or endmill up and down in Z and moving the material laterally in X and Y (see Figure 4-12). Most simple component shapes can be machined in this fashion, but since only one side of the material is exposed to the cutting tool, some parts require double sided machining. This requires removing the blank from the fixture, inverting it, then realigning and restarting the machine. For example, a cone or pyramid could be machined from the top, whereas a sphere would have to be machined from two sides. If possible, parts were designed for single-sided machining to reduce manufacturing time and complication. This was not always possible, for example, the Whegs™ wheel-legs require double sided machining. By placing component sets as close together as the tool diameter would permit, wasted material was minimized. After CNC machining, hand operations were necessary to remove the parts from the material blanks, add and tap holes, etc.



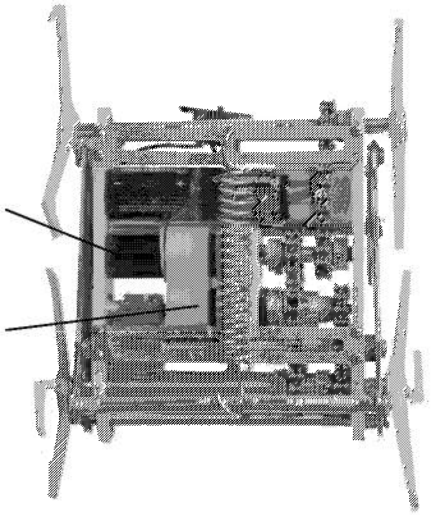


Figure 4-10. Layout of Mini-Whegs™ 3. **Figure 4-11. Layout of Mini-Whegs™ 4J.**

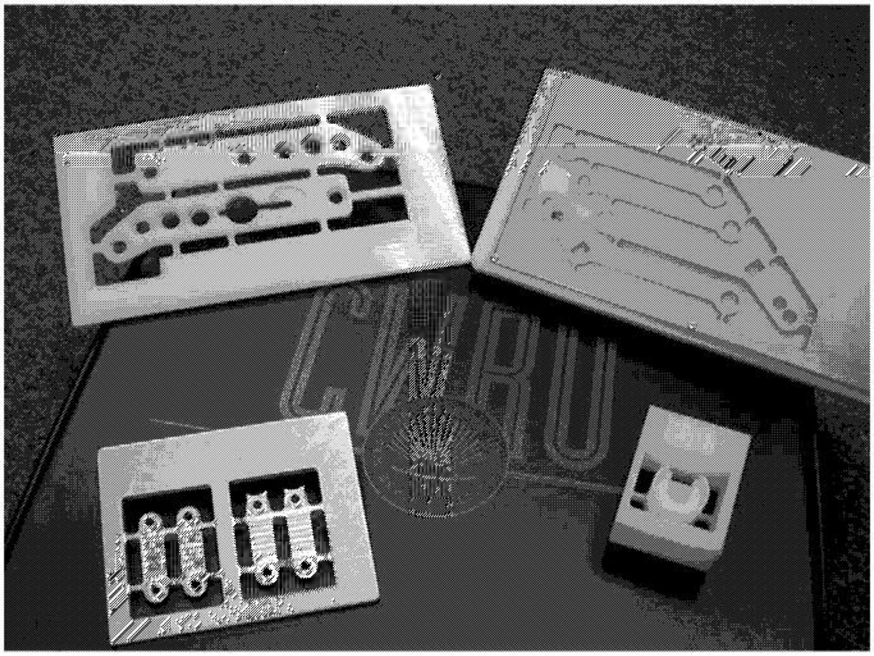


Figure 4-12. CNC machined parts for MW-4J before removal from surrounding material.

Mini-Whegs™ 4J and subsequent robots were modeled in Pro/ENGINEER prior to construction to confirm the validity of the designs and determine possibilities for improvement. The use of the software was necessary to create CNC manufacturing files for individual components, while the creation of a complete robot assembly greatly aided in overall design visualization. In many cases, more suitable design solutions were created based on examination of the 3 dimensional computer models.

4.2.5 Control System and Operation

Most Mini-Whegs™ robots are user controlled via a receiver and remote transmitter. For the purposes of proving the jumping concept, Jumping Mini-Whegs™ was designed without any steering ability or active control system. Control and actuation of jumping are accomplished mechanically via the slip-gear mechanism. The robot is simply turned on with a switch and then it automatically runs, jumps, and repeats until it is turned off.

4.3 Results

Jumping Mini-Whegs™ was designed to prove that jumping capability could be achieved on a small-scale robot to improve mobility over obstacles of large relative size. The robot can leap 9 inches (22cm or 2.5 body lengths) high, which is greater than the height of one standard stair. The robot's single motor powers both running and jumping functions simultaneously. While the robot runs, energy is slowly stored in the spring as the four-bar mechanism is retracted over the period of approximately one minute. When the discontinuity in the slip-gear is reached, the jumping mechanism is released. After the jump, the robot continues running while the mechanism is again retracted.

The arrangement of the four-bar mechanism permits a variety of spring sizes, stiffnesses, and preloads to be characterized. As determined in Section 3, the most successful mechanism uses a relatively soft spring with significant preload in order to store and release the maximum possible energy for the jump, given a certain maximum available motor torque.

The initial jump trajectory was nearly vertical and therefore poor for clearing obstacles. This was due to the orientation of the four-bar mechanism at the time of contact with the ground, relative to the center of mass of the robot. Since contact occurred almost directly below the center of mass, it was determined that moving the point of contact slightly rearward would create a more desirable forward and upward trajectory. Instead of reconfiguring the four-bar mounting points or dimensions, a simple and effective solution was devised. The feet were redesigned with small spiked heels, which serve the dual purpose of moving the ground contact point rearward, as well as increasing traction.

Jumping Mini-Whegs™ demonstrated that jumping could be achieved on a robot of this scale, and that the same motor could power both running and jumping. As such, the repeated running / jumping sequence is not flexible and actuation thereof is not independent. In order for independent and controllable operation to be achieved, a separation between the two functions will be necessary.

Jumping Mini-Whegs™ is designed to run either upright or upside down, but only jumps when upright. When the robot lands from a jump in that same upright orientation, it cannot run with full effectiveness until the four-bar mechanism is retracted most of the way. If the robot lands in an inverted position, it can run unhindered as the mechanism retracts, but cannot perform its next jump unless it is righted.

5. MINI-WHEGS™ 5 DEVELOPMENT

5.1 Introduction

Mini-Whegs™ 5 (see Figure 5-1) is similar in design to the earlier MW-1 and MW-3 robots. It is designed to be robust and functional with a variety of incremental performance improvements over its predecessors. Jumping ability was not implemented into this vehicle. Specific goals included enhanced forward and reverse (bi-directional) control, more consistent locomotion over a variety of surfaces, and improved handling and steering ability. Characteristics such as compactness and minimal weight were obviously desirable, but the majority of design work focused on increasing its functionality and robustness. As such, the robot is slightly larger and heavier than Mini-Whegs™ 3.

5.2 Design

5.2.1 Improved Whegs™ Wheel-Leg Appendages

In Mini-Whegs™ 5, the wheel-legs are each machined from a single piece of Delrin (see Figure 5-2). This design allows for a certain amount of compliance under normal operation due to the flexible polymer material and slender spokes. Earlier robots in the series used rigid wheel-legs fixed to the central axle through a flexible coupling system, similar in concept to that on the full-sized Whegs™ robots. This mechanism allowed a limited amount of torsional compliance between the axle and wheel-legs, but at this small scale the coupling was subject to failure under the high loads experienced during climbing. It was also not clear that any climbing mobility was gained by the use of the devices on Whegs™ robots on the scale of MW-1, 2, and 3. For these reasons and to provide more robust construction, the axial-based torsional compliant couplings were removed from the design.

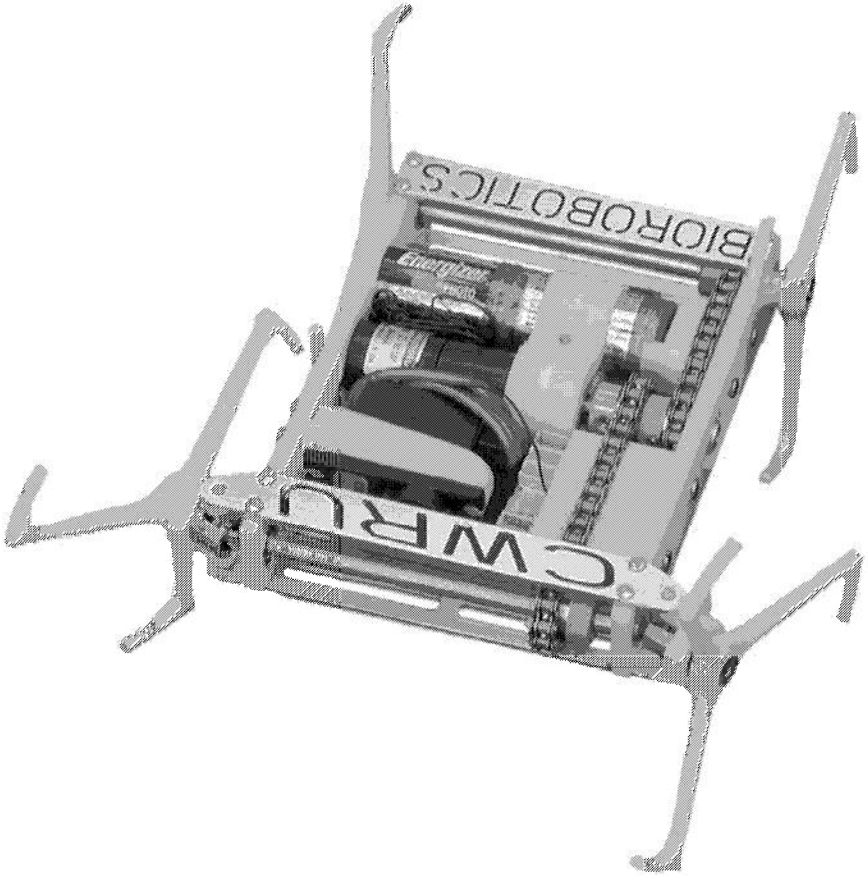


Figure 5-1. The Mini-Whegs™ 5 robot.

Original wheel-leg designs used a sharp tipped foot, which penetrated carpet and other yielding surfaces to provide good traction. However, this foot sometimes snagged on the substrate and caused the vehicle to somersault into the air. Since more consistent operation is desired, the modified design of the wheel-legs (see Figure 5-2) allows for more surface area by adding a small foot, which consists of an arc segment that follows the circumference of the wheel-leg. Theoretically, the length of each foot could be increased from 0 to 120 degrees - - in other words, from bare spokes to a complete wheel. However, as the length of the foot is increased, the climbing ability of the robot is diminished. In the limit, it would provide the speed and smooth ride of a wheel, but also with the poor climbing performance of a wheel. A short segment length of 25 degrees was chosen to provide enough surface area to prevent snagging on softer surfaces without sacrificing significant climbing ability.

While the spokes of the rear wheel-legs occupy a purely vertical plane, the front ones are splayed outward so that they rotate in a cone (see Figure 5-2). This design allows for greater clearance of the frame of the robot for a tighter turning radius. Additionally, a slight splay aids in the lateral stability of the robot by widening its stance. Full et al. describe the advantages of such a sprawled posture in cockroaches [8].

5.2.2 Steering

The basic design of the steering mechanism for Mini-Whegs™ is similar to the system in an automobile. Each front Wheel-leg rotates in a bearing, which is supported by a steering arm. A servo actuated sliding rack connects to the steering arms with a slot and pin. The steering arms pivots in mountings on the aluminum chassis cross-braces to provide a steering motion. A rendering of the steering layout for Mini-Whegs™ 5 is shown in Figure 5-3.

Since all four wheel-legs are driven, the front axle must transmit power to the wheel-legs and still allow for steering movement. Flexible materials were explored for this application in earlier versions of Mini-Whegs™. As discussed in Section 2, these components were designed to serve the dual purpose of providing torsional compliance for automatic gait adaptation, but were too often subject to failure. Mini-Whegs™ 5 forgoes axle-based torsional compliance for greater precision and strength.

To provide a strong and reliable steering system for Mini-Whegs™ 5, a simplified universal joint was designed for each front Wheel-leg using no flexible components (Fig. 5-3). The joint consists of a ball at either end of the front axle inserted into a brass cup, which is mounted in the steering arm bearing. A pin attached to the ball slides in a slot in the brass cup to transfer torque while allowing the cup to pivot around the ball. Dimensions of steering arms and other components were optimized to allow the maximum pivoting travel given certain clearance and servo travel limitations.

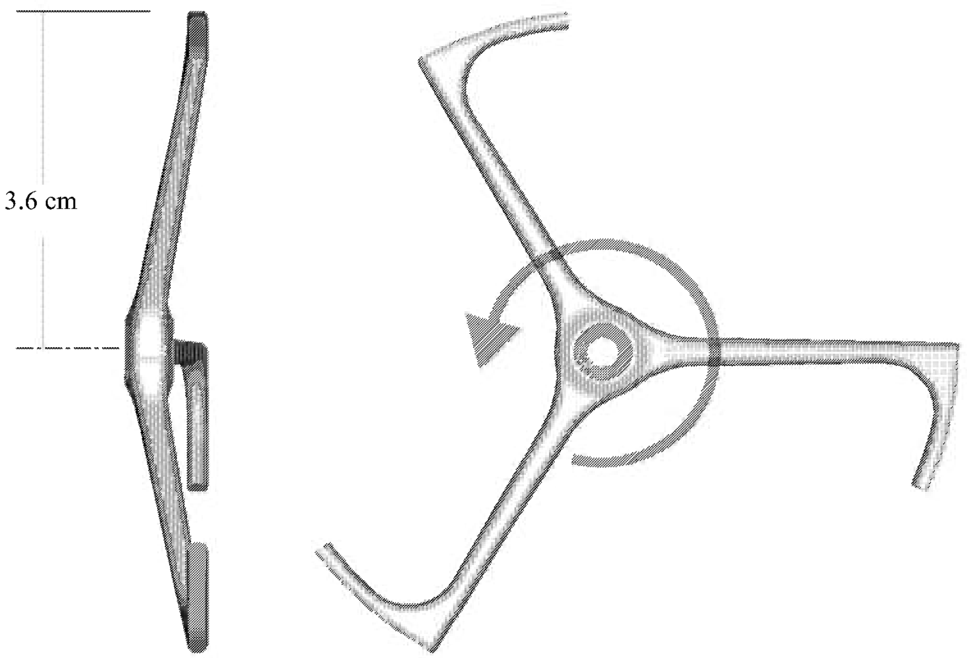


Figure 5-2. Front Wheel-leg design of MW-5, showing feet, lateral splay, and direction of rotation.

The new turning radius averages 9 inches (22.9 cm) or 2.5 body lengths, which is perhaps 50% of the radius of robots using the previous steering designs. This is for two reasons. In old designs, the micro-servo had to exert a large force at extreme steering angles to bend the couplings which caused reduced motion. Also, analysis was performed on the new design to optimize dimensions of components to achieve maximum steering range for a given available servo travel.

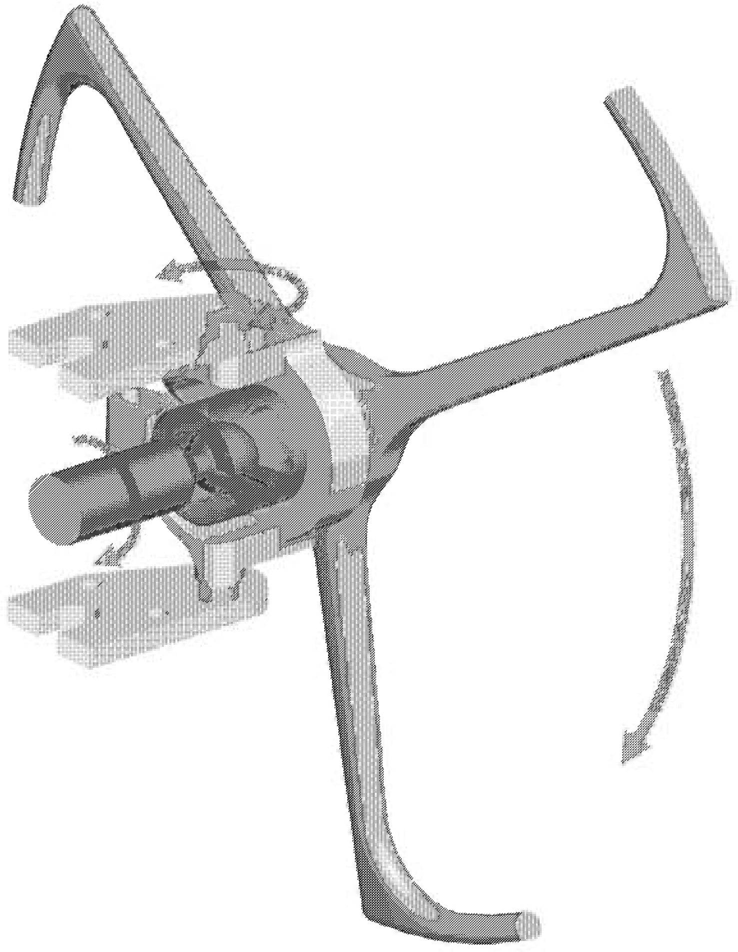


Figure 5-3. Rendering of the Mini-Whegs™ steering components.

5.2.3 Chassis

The basic rectangular frames of Mini-Whegs™ 1, 3, and 5 are very similar. In designing the frame, spacing between components must be considered carefully because of the robot's compact design. Components are placed according to a variety of factors including motor and sprocket diameters, finite chain spacing increments, weight distribution, and a variety of precise clearance requirements. The cross-braces also support the steering arms and they are machined from 0.50" (0.127 cm) thick aluminum.

The physical dimensions of the Mini-Whegs™ 5 chassis are 3.6" long by 2.7" wide by 0.8" thick (9.0 x 6.8 x 2.0cm) with attached 1.4 inch (3.6cm) radius wheel-legs. The robot is slightly larger and heavier, at 146g, than the previous comparable robot, MW-3.

Mini-Whegs™ 5 (see Figure 5-4) uses essentially the same off the shelf components as previous robots in the series. These include the 1.2W 13mm diameter Maxon motor and attached 67:1 transmission, Cirrus CS-10BB micro-servo, two 0.1475 pitch sprocket/chain sets, and two 3V CR2 batteries.

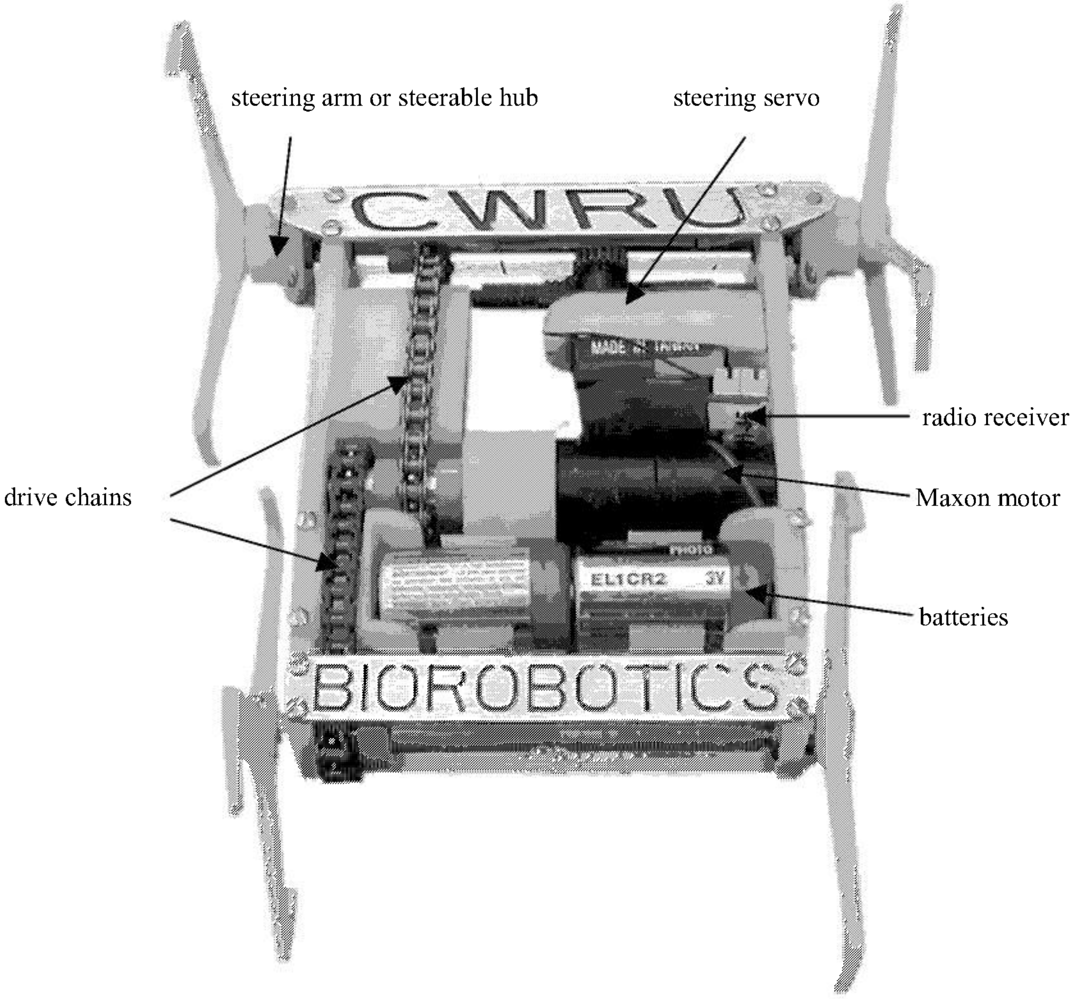


Figure 5-4. Component layout of the Mini-Whegs™ 5 robot.

5.2.4 Control System and Operation

Control of Mini-Whegs™ 5 is accomplished via a four-channel RC transmitter and a sub-micro four-channel Sky Hooks & Rigging RX-72 receiver. For the first time in the series, a separate SCWES-5Bi speed controller (see Figure 5-5) is employed for bi-directional throttle control. Previous robots in the Mini-Whegs™ series used a RX-72HYB receiver with integrated speed controller, which only provided throttle control in the forward direction. This very small (5mm x 19mm x 19mm, 1.7 g) component did not necessitate increased frame dimensions.

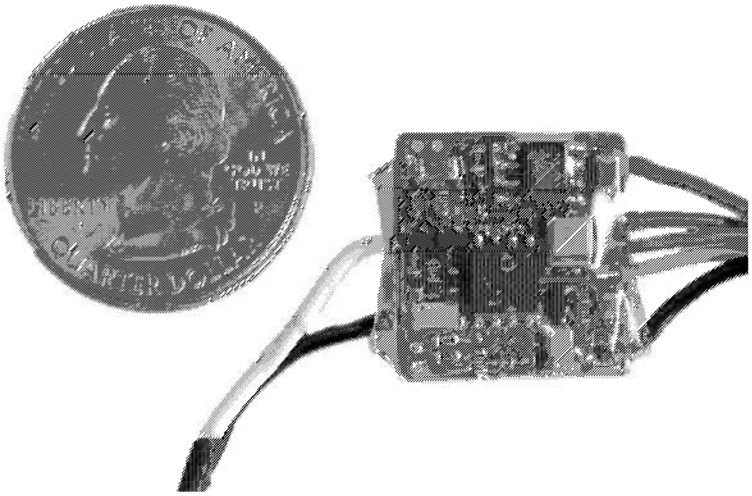


Figure 5-5. The SCWES-5Bi speed controller improves control of MW-5.

5.3 Results

Mini-Whegs™ 5 is a successful design, incrementally improving upon the features and performance of previous Mini-Whegs™ robots. Like the high-speed performance of other Mini-Whegs™ robots, the 3.6 inch long Mini-Whegs™ 5 can run at over 10 body lengths per second and can run over obstacles of height greater than the radius of the wheel-legs (see Figure 5-6). No reduction of climbing ability was observed with the removal of torsional compliance. Improvements in performance include more consistent running behavior (no flipping), more versatile bi-directional control, reduced turning radius, and better traction on soft surfaces.

The new wheel-leg design allows Mini-Whegs™ 5 to excel in rough terrain such as dirt or grass, where speeds nearly as high as those on smooth terrain are observed. The robot has been documented to run for extended periods of time through grass higher than the top of the chassis [14]. The new wheel-legs also reduce the previously documented (Section 2) flipping behavior. More consistent running performance is achieved through the addition of feet, which do not penetrate carpet, etc., as did the previous designs that featured sharp tipped wheel-legs.

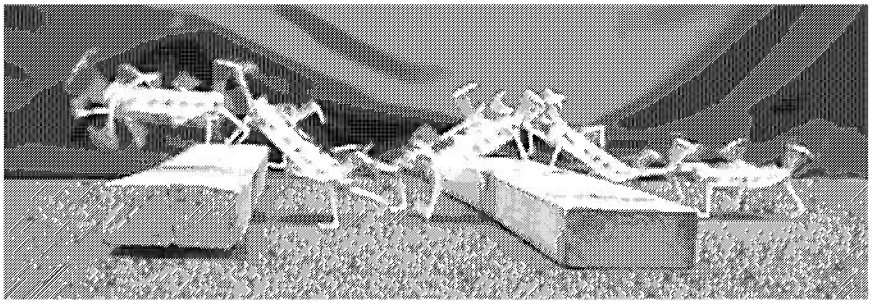


Figure 5-6. Composite of video frames showing Mini-Whegs™ 5 traversing two 1.5 inch high by 3.5 inch wide obstacles while running at 3 body lengths per second.

The only discernable disadvantage of the added feet is the increased possibility of catching or hooking tangled materials during the upswing of the Wheel-leg after ground contact. This behavior was possible with older Wheel-leg designs, but less likely because of the straight spokes and lack of curved feet. However, in testing on a variety of surfaces over extended periods of time, this problem was rarely encountered. In most cases, the robot could be reversed out of the tangled obstacle. The overall highly successful Wheel-leg design first implemented on MW-5 was soon retrofitted to both Mini-Whegs™ 3 and Mini-Whegs™ 4J.

The turning radius averaged 9 inches or 2.5 body lengths (22.9 cm), which is 50% smaller than the turning radius of the previous steering designs. Because the ball and cup design was so successful in Mini-Whegs™ 5, Mini-Whegs™ 3 was retrofitted with the same steering system.

In addition to being extremely mobile, Mini-Whegs™ 5 is also robust and versatile. It has been dropped from a height of 10 or more body lengths, and has tumbled down flights of concrete stairs with no damage. Like other Mini-Whegs™ robots, it can operate while inverted.

Performance issues include an intermittent “freezing” of the forward motion of the robot, which has proven difficult to characterize and eliminate. Testing suggests that the behavior is the result of the speed control circuit becoming unresponsive to throttle control inputs. A wiring setup, not unlike a leash, was constructed to facilitate dynamic measuring of voltage and current at various points in the electrical system. Results indicate that the problem could, in fact, be some type of mechanical catching in the drive train. When the motor becomes stalled, a current spike may overload the speed controller, causing it to stop functioning. To restart the speed controller, a control discontinuity, i.e., flipping the throttle to reverse then back to forward, is necessary to reset the mechanism. Thus, the issue is not a fatal performance flaw, but a nuisance behavior. By systematically eliminating potential obstructions in the drive train, it was determined that stalling may be due to unknown damage or a defect in the internal components of the Maxon transmission.

6. CONCLUSIONS AND APPLICATIONS

6.1 Conclusions

Mini-Whegs™ robots are small, durable and highly mobile vehicles. They can be mass-produced to perform missions as individuals or in groups. Figure 6-1 shows that Mini-Whegs™ 5 is not much larger than a *Blaberus gigantius* cockroach. Therefore, it can move stealthily through complex terrains to perform tasks such as reconnaissance. Furthermore, the vehicles can be made even smaller because of their relatively simple design.

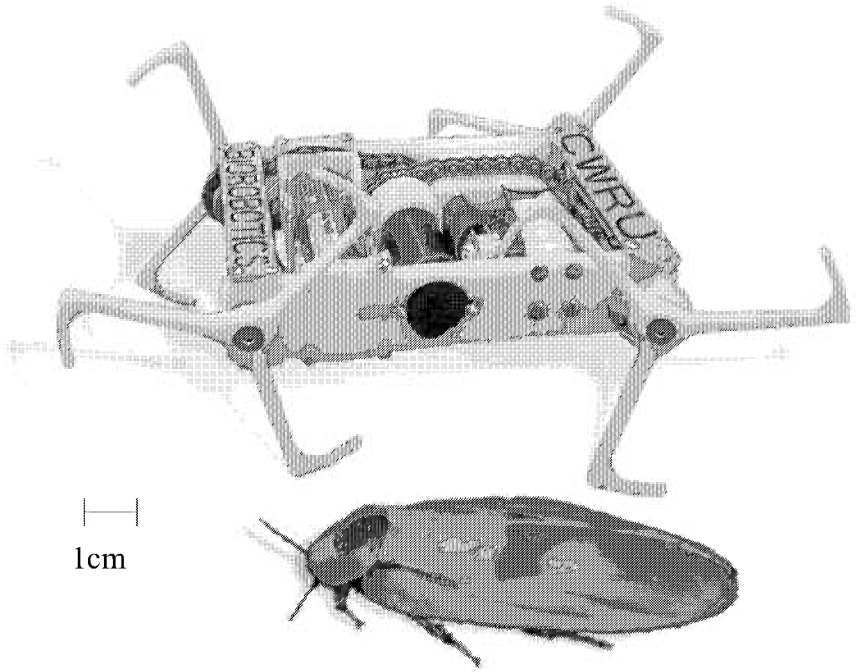


Figure 6-1. Photograph showing relative sizes of the Mini-Whegs™ 5 robot and a *Blaberus gigantius* cockroach.

The primary advantage of wheel-legs over wheels is increased mobility on uneven terrains. Advantages over other means of legged robot locomotion include mechanical and control simplicity and far higher speeds. In addition to being maneuverable and capable of surmounting large obstacles, the 9cm long Mini-Whegs™ robots can run at over 10 body lengths per second (90cm/s). Because of the three-spoked Wheel-leg geometry, a Mini-Whegs™ robot can climb over obstacles 1.5 times as tall as the radius of the wheel-legs. The same robot, fitted with wheels instead of wheel-legs for comparison, runs 50% faster on smooth terrain, but is stopped by obstacles less than one radius high. Mini-Whegs™ excels in rough terrain such as dirt or grass, where speeds nearly as fast as those on smooth terrain are observed. The reduced speed of Whegs™ locomotion versus wheels on smooth terrain is a worthwhile tradeoff for its increased mobility.

Relative to body length, Mini-Whegs™ robots are significantly faster than other legged robots [19]. Their design allows each leg to swing higher than the body so greater obstacles can be surmounted. Not only are Mini-Whegs™ robots faster and more mobile than other legged robots, they are power autonomous and are operated remotely using wireless communications.

In addition to being extremely mobile, Mini-Whegs™ are also robust and versatile. These lightweight robots have been dropped from a height of 10 or more body lengths, and have tumbled down flights of concrete stairs with no perceptible damage. Because of the low profile of the robot frame, Mini-Whegs™ can also operate while upside down, if necessary. While inverted, radio control becomes less intuitive, and traction is somewhat reduced due to the less-suitable foot and steering orientation. In order to return the robot to normal upright operation, the operator can simply drive the vehicle into a large obstacle, so that it flips over again.

Tests demonstrate that Jumping Mini-Whegs™ can leap 22cm (2.5 body lengths) high, which is greater than the height of one standard stair (see Figure 6-2). The automatically resetting mechanism for repeated jumping works consistently and reliably once properly calibrated. The mechanism uses a linear spring with significant preload to store energy for the jump.

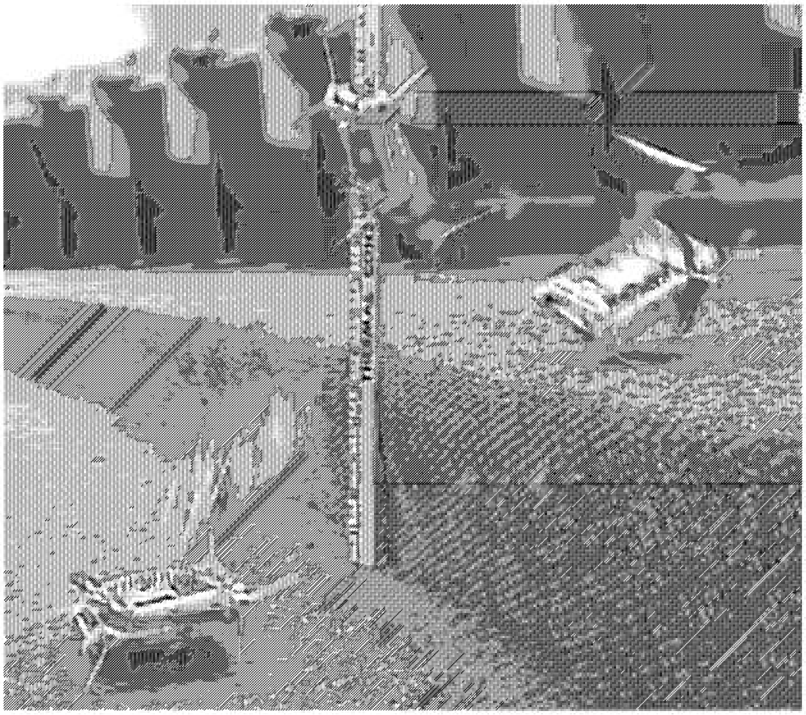


Figure 6-2. Composite of video frames showing Jumping Mini-Whegs™ clearing a 6-inch high stair.

Because of its straightforward design, a Mini-Whegs™ robot is easy to operate. A small switch turns on the robot and a radio control transmitter is then used to control steering and throttle. The turning radius for MW-5 using wheel-legs, averages the same as the turning radius using wheels - 2.5 body lengths (22.9 cm). MW-4J is fully automatic once turned on, and does not have steering capability.

Though never precisely quantified, life of the CR2 lithium batteries has proven significant. Under continuous use, we expect they will last a minimum of several hours. Because of the high current drain experienced while winding the spring in the jumping robots, somewhat less life is observed.

Mini-Whegs™ has difficulties traversing certain materials, primarily those that allow the wheel-legs to penetrate and catch, such as slatted surfaces or tangled obstacles such as brush or cable, which can get caught in the wheel-legs. In some sense, the issue of catching could perhaps be considered inherent in legged vehicles and creatures, however this problem appears to be accentuated by the rotational motion of the wheel-legs. In testing on a variety of surfaces over extended periods of time, this problem was rarely encountered. In many cases, the robot could be reversed out of tangling obstacles.

The robot also has difficulty moving quickly over hard or polished surfaces. An analogy could be drawn with movement patterns of animals on ice, i.e. slow movement is possible, but acceleration becomes difficult due to low available traction. In the case of Mini-Whegs™, this slipping is caused by the low friction coefficient of the Delrin material used in the wheel-legs on hard and polished surfaces. Whegs™ ASP, a larger hexapod Whegs™ vehicle, has similar shaped feet that are coated in rubber, which enables them to grip smooth and hard surfaces [9]. Versions of mini Whegs™ under development will also use feet coated with a thin layer of high friction material to allow greater operating speeds on these surfaces, with no negative effects on softer surface traction.

In future work, a fully functionally running, jumping, and steerable Mini-Whegs™ robot will be developed. The robot will combine the functionality of all previous Mini-Whegs™, while adding remote control operation of both the running and the jumping modes of locomotion. Since all essential systems have been tested and previously proven, success of the robot is anticipated.

6.2 Applications

The uses of a small, highly mobile robots such as Mini Whegs™ are numerous. Long-term goals of the Mini-Whegs™ robots include providing a highly mobile platform for intelligent and autonomous control. Mini-Whegs™ robots can carry more than twice their own body weights in payload, so they are suitable platforms for testing sensor and control packages. Mini-Whegs™ could serve in a variety of applications, including roles in reconnaissance, surveillance, search and rescue, and space exploration. Furthermore, they could work in teams to greatly enhance their capabilities. With future work, they could be made very cheaply in high volume batches so that it would be practical to use them in large groups and a single vehicle could be considered expendable.

A more mobile small robot platform could be useful for research in insect inspired navigation, for which mainly small, wheeled robots are currently used. Full sized Whegs™ robots have already been successfully used as outdoor sensor platforms [9]. However, in some cases a small robot is preferable to fully investigate certain biological phenomena, e.g. cricket phonotaxis. Mini-Whegs™ and Jumping Mini-Whegs™ provide viable and highly adaptable platforms for outdoor locomotion.

In a recent Case Western Reserve University master's project, a wireless personal digital assistant (PDA) and control board were mounted on the Mini-Whegs™ 5 chassis [10]. The PDA communicates with a laptop computer via an 802.11b wireless Ethernet connection. A user can control MW5's motor and steering servo remotely from the laptop. The PDA and other onboard electronics include many surplus available resources for potential sensor integration and other future functionality.

In conclusion, Mini-Whegs™ is highly mobile and durable robot platform with great potential for use in many missions. The simple and inherently rugged design of the robot lends itself to inexpensive and straightforward manufacturability. Its unique combination of robustness, speed, and running and jumping mobility is superior to other robots of similar size, which makes it most suitable for many missions that are best served by a small robot.

7. REFERENCES

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