Chaos an Intelligent Ultra-Mobile SUGV: Combining the Mobility of Wheels, Tracks, and Legs

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ABSTRACT

Autonomous Solutions has developed Chaos, a small unmanned ground vehicle with four modular running gear receptacles. Running gear attached to the vehicle can include any combination of wheels, tracks, articulated and shape-shifting tracks, and legs. Each unit is independently controllable and field changeable. This modular design allows *Chaos* to combine the strengths of traditional and bio-inspired locomotion. The vehicle offers unprecedented mobility potential including walking, stair climbing, clambering over obstacles, steep slope traversal and extrication. To fully exploit the vehicle's mobility potential, intelligent behaviors must be integrated to reduce the complexity of vehicle operation. Mobility behaviors include operator assisted tele-operation, adaptive gaits, obstacle characterization, traversal, and extrication. This paper will describe the design and development of Chaos including running gear and intelligent mobility behaviors.

Keywords: Small Unmanned Ground Vehicle, SUGV, Vehicle Mobility, Bio-Inspired Mobility, Bio-Inspired Robotics, Unmanned Ground Vehicle, UGV, Robotics, Intelligent Behaviors, Semi-autonomy, Articulated Tracks, Walking Robots

1. INTRODUCTION

Chaos, is a small unmanned ground vehicle (SUGV) designed as a platform for search, reconnaissance and surveillance in unstructured and destructured environments. Chaos has been designed from the ground up to provide unparalleled mobility and allow for further mobility options to be quickly and easily integrated with the vehicle.

A key component to the vehicles mobility is its modular running gear. Four dual-drive receptacles on the vehicle allow for quick attach and detach of various types of running gear. Examples of running gear include: tracks, wheels, legs, arms, articulated tracks, and shape shifting tracks. Vehicle running gear may be mixed and matched to meet a variety of operational needs. Because of its ability to quickly change methods of locomotion, Chaos is able to effectively operate in a wide range of situations and missions.

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Versatility is a major strength of the vehicle. However, such versatility can quickly make for complex operational requirements and an increased burden on the vehicle operator. To mitigate the increased complexity of the system, Chaos utilizes operator assist software that allows complex functions to be automated or simplified. This software allows a user to easily tele-operate the vehicle without concern for how the motion is accomplished at a low level. For example: regardless of running gear configuration, to move the vehicle forward, the user merely pushes the joystick forward and the vehicle moves in the desired direction coordinating the movement of the low level hardware to accomplish the motion.

In addition to operator assist, Chaos is currently being outfitted for semi-autonomous operation in cluttered environments. Using sensor feedback Chaos will be able to detect terrain and utilize appropriate behaviors to overcome obstacles. Examples of behaviors include: real-time adjustment of track angle and speed, track walking patterns or gaits, self leveling, trajectory tracking, and self extrication maneuvers.

2. BACKGROUND

The original idea that led to the development of the Chaos robot was conceived by Mel Torrie, now CEO of Autonomous Solutions. According to Mr. Torrie the idea came from the desire to combine the strengths of walking, wheeled, and tracked vehicles. Legged vehicles have the ability to traverse uneven and rugged terrain, tracked vehicles provide high friction in loose or slippery terrain and low ground pressure, while wheeled vehicles are more efficient and faster on level terrain. Mr. Torrie reasoned that a vehicle that could combine these forms of locomotion would have unprecedented mobility in almost any kind of terrain. In September of 1998 Mr. Torrie began making sketches in his planner of the vehicle that would eventually become Chaos (see Figure 1).

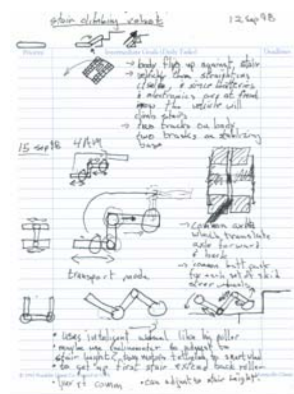

Figure 1 - Initial Chaos Concept Sketches

Mr. Torrie also started experimenting with components from off the shelf toys and household items to test out the idea (see Figure 2). Later, he used Legos® to create a high-level conceptual prototype of the vehicle (see Figure 3).

Figure 2 - Homegrown Chaos Track

Figure 3 - Lego Chaos Prototype

As the idea progressed it was refined by others including Mitch Torrie, Brett Thayn and Dr. Kevin Moore. They took the idea to local law enforcement and asked for direction in creating a product they could sell. From their research and work came a rough set of dimensions for the vehicle from which they built a set of Styrofoam mockups to scale (see Figure 4) and continued to refine the design with the help of local law enforcement.

Figure 4 - Styrofoam Mockups

Once they had an appropriate sized design, they used advanced modeling software to simulate the vehicle in rough terrain and further refine the design (see Figure 5). Simulating the vehicle gave them a good idea of how the vehicle would perform in real world conditions without the expense of producing an untested prototype.

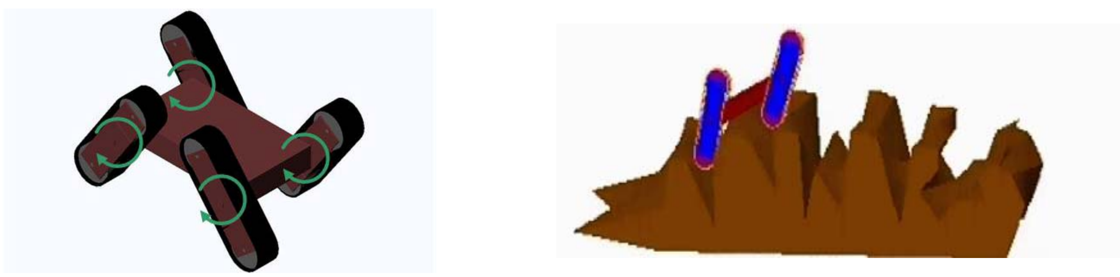

Figure 5 – Software Simulated Chaos

In the spring of 2000 funds were secured for a functional prototype developed in a partnership between Autonomous Solutions and Dr. Kevin Moore. The first functional prototype was built for under $6,000 in less than 3 weeks. The robot was demonstrated at the June 2000 NIJ/OST Annual Technology Conference in Denver Colorado. It was an invertible design that used actuated walking beam tracks to achieve high mobility relative to its physical size. Figure 6 shows the original functional Chaos prototype.

Figure 6 - First Functional Chaos Prototype

Over the next two years the initial prototype was shown to potential customers in law enforcement and the military. Unfortunately no funding was secured to further the development of Chaos to a commercial quality robot.

Finally the Chaos robot idea was proposed to TARDEC in response to an SBIR solicitation on the topic of small vehicle mobility. The idea of Chaos was well received and TARDEC eventually funded it through the SBIR program.

3. GOALS AND OBJECTIVES

The goal of the SBIR contract is to develop, demonstrate, and test a man-packable SUGV that can fill important and distinctive functions in the context of military physical security and homeland defense.

High-mobility man-packable SUGVs are needed to support troops in advance security, screening and reconnaissance operations in and around buildings, and close, urban areas. The SUGVs need to be able to operate effectively in unstructured and destructured environments of urban and village battle zones. These SUGVs need obstacle-crossing capabilities comparable to dismounted troops. They need a small profile so they can maneuver without being seen (thus maintaining operational security), and to enter crawl spaces and negotiate gaps in debris. They need to be rugged enough to be thrown over a wall or through a window. These SUGVs may be used to deliver non-lethal incapacitation agents or ordnance, to deposit stationary surveillance units, or to conduct search and reconnaissance. SUGVs with these capabilities will have a potential role in the search for survivors in collapsed or damaged buildings, establishing auditory contact, and possibly delivering small quantities of medical supplies.

4. DEVELOPMENT STRATEGY

The challenge is to refine and re-engineer the Chaos design to produce a low-cost, rugged practical vehicle that meets the performance requirements of the customer. To accomplish this objective a spiral model approach was taken in which many rapid development iterations are used to refine the vehicle design. This process allows us to quickly evaluate performance changes and different designs in a short period of time. Each new prototype developed is a complete SUGV with full implementations of most of the critical subsystems including:

- Locomotion (running gear, drive, motors, torque converters, low level motor control)
- Chassis (internal and external configuration, and materials)
- Power (power supply, power management, recharging)
- Sensors (video, inertial sensors, odometers, proprioceptive sensors, etc.)
- Communications (video from SUGV to base, and bi-directional data communication)
- Behavior hardware and software (translating instructions into motor control primitives)
- Operator interface (control unit, I/O modes, and command and control instructions)

The principle elements of the design approach are:

- Start with a proven and effective design
- Rescale the design to meet the specific performance goals
- Rapidly fabricate a prototype
- Test and refine the prototype.
- Repeat

By building on prior experience, we can employ rapid prototyping and physical testing to evolve the vehicle through multiple iterations within the project time frame.

5. DESIGN FOR MOBILITY

Traditional approaches to off-road mobility for military, construction and agricultural vehicles rely on large wheels or tracks. While suitable for large vehicles, this approach does not scale down to provide comparable mobility for small vehicles. Obstacles that a large vehicle can simply run up and over (logs, small boulders, and meter-wide gaps) are just part of the surface texture to a large tracked vehicle, but are discrete geometric obstacles for a small vehicle. Relative to the vehicle size, the obstacle-crossing requirements for a small vehicle in an urban war or natural disaster zone are more severe than the obstacle-crossing requirements of traditional manned vehicles.

The unmanned ground vehicle (UGV) design space is more open than that of manned vehicles. UGVs are not required to have a crew compartment. UGVs can tolerate roll and pitch motions, including inversion, that would be dangerous for a crew. UGVs can employ locomotion mechanisms with articulated limbs and/or bodies that require more complex computer control than simple steering, brake and throttle controls of manned vehicles.

TARDEC is actively engaged in the research and development of SUGVs weighing less than 50 kg for physical security and force protection applications. The physical design considerations that govern the development of large ground vehicles do not apply to the SUGV of interest to TARDEC. When a vehicle design is scaled up by a factor of X, the area increases in proportion to X^2 and the weight increases in proportion to X^3, thus the ground pressure increases in proportion to X. Similarly, the length of a beam or arm increases in proportion to X, but the forces it must support increase in proportion to X^3, thus the strength of the beam or arm must increase in proportion to X^2.

For these reasons, the design space for SUGVs is considerably more open than that of medium and large UGV and manned vehicles. A variety of different locomotion approaches are being explored under TARDEC sponsorship. These include walking machines, SUGV with rotating curved legs instead of wheels (e.g., Rhex), and tandem vehicle systems (e.g. as demonstrated by Turing Associates). Prototype omni-directional vehicles (ODV), hybrid legged ODV, and hybrid tracked-walking SUGVs have been developed for TARDEC by Autonomous Solutions in conjunction with Utah State University.

6. LOCOMOTION

Chaos is able to utilize different forms of traditional and bio-inspired locomotion via field swappable running gear. The quick attachment / detachment of modular running gear allows the vehicle to be optimized for a specific scenario or mission and increase the utility of the vehicle over a broad spectrum of operational conditions.

6.1 Tracks

Tracks provide good traction in loose soil, low ground pressure and increased surface area. This increases the capability of the vehicle to operate in areas where traction is limited, but leads to inefficiencies on hard smooth surfaces and may be inadequate in highly cluttered environments. With tracks attached locomotion is accomplished via skid steer. Due to the dual drive system, the tracks can be driven by either of the two motors. Using the walking drive, the tracks have increased torque, but a lower top speed. Using the track drive, the tracks have a higher maximum speed, but lower torque.

Figure 7 - Chaos with Tracks

6.2 Wheels

Wheels provide better efficiency and higher speed on hard uncluttered surfaces. This increases operational range of the vehicle over smooth ground. However, wheels do not provide adequate traction in loose soils or highly cluttered environments. In this configuration the vehicle maneuvers via skid steer rather than Ackerman. Again due to the dual drive system the wheels can be driven by either of the two motors to achieve a desired speed / torque ratio. It is also conceivable to utilize one or more of the drive mechanisms to steer the wheels thereby allowing for Ackerman or crab steering.

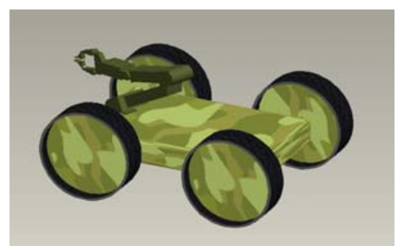

Figure 8 - Chaos with Wheels

6.3 Legs

Legs provide better mobility in highly cluttered environments. However, legs are less efficient and more difficult to control precisely. Legs may also have more difficulty navigating steep slopes than wheels or tracks. In the legged configuration the vehicle maneuvers via quadrupedal motion by coordinating the movements of all four legs simultaneously. Turning is accomplished by slowing the rate of movement on a side (similar to skid steer movement). This leads to large turns (increased turning radius) that may be slow to effect. Stepping over obstacles can be accomplished by rotating one leg independently of the others and then continuing with coordinated motion.

Figure 9 - Chaos with Legs

6.4 Walking Articulated Tracks

Figure 10 - Chaos with Walking Articulated Tracks

Walking articulated tracks allow active control of track beam speed and position in addition to the standard track drive. Using this configuration it is possible to combine the strengths of tracks, wheels, and legs in a single set of running gear. Each track is driven independent of the track beam. Track beam movements can be coordinated to achieve different vehicle gaits such as undulating, crawling, waddling, flailing, and other behaviors. Track beam movement and track movement can also be coordinated to modulate or accentuate speed. In this configuration locomotion is accomplished via skid steer and/or quadrupedal motion. During skid steer operation the amount of frictional forces on the terrain can be changed by altering the position of the track beams, thus increasing efficiency close to that of a wheel. As the track beam ends on one side move closer to one another the effective wheelbase of the vehicle shortens further decreasing frictional resistance to turning. In our testing of the Chaos vehicle the walking articulated tracks have been found to be the most mobile and versatile configuration.

6.5 Passive Beam Quad Tracks

Figure 11 - Chaos with Passive Beam Quad Tracks

This configuration is similar to the walking articulated track configuration except that each track passively pivots in the center. The passively pivoting tracks conform to uneven terrain, maximizing surface contact area and evenly distributing load. This minimizes ground pressure, sinkage, and ground resistance on soft soils. Vehicle ground clearance is increased due to leverage on the track beams. Passive motion is achieved by mechanically disengaging the track beam motors or by not sending commands to the motors and allowing them to be back driven by terrain forces.

6.6 Shape Shifting Tracks

Figure 12 - Chaos with Shape Shifting Tracks

Shape shifting tracks can change from a track to a wheel configuration and vice versa without modification to the vehicle. This approach effectively provides a two speed transmission and an on/off road running gear (see Figure 12). In track mode, the track can be driven around the tensioning arms while the tensioning arms pivot to conform to the terrain. In wheeled mode, the vehicle is capable of high speed on hard, flat terrain. The vehicle uses ordinary tracked mode for soft soils and low-friction surfaces.

7. DESIGN ITERATIONS

The Chaos SUGV has undergone several design iterations and will continue to evolve as new ideas are prototyped and tested until the vehicle is polished and meets customer requirements. To date four prototype vehicles have been fabricated for testing and evaluation since the first prototype was developed. This brings Chaos to the fifth revision. Testing and customer trial of each prototype has continued to refine the design toward a commercially viable SUGV (see Figures 13 – 16)

Figure 13 – Chaos Prototype # 2

Figure 14 - Chaos Prototype # 3

Figure 15 - Chaos Prototype # 4

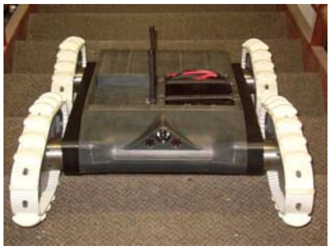

Figure 16 - Chaos Prototype # 5

Of the vehicle components currently under refinement, the following have received the most attention to date – The modular drive units, the track, the vehicle body, and the battery and payload bay.

7.1 Modular drive units

Developing modular drive units that can provide torque and power to a variety of field swappable running gear has been a challenging process. At each corner of the vehicle, rotary power must be available for two functions simultaneously. The most common configuration is for a high speed, low torque drive function and a low speed, high torque walk function. These two functions are provided by two concentric shafts at each corner of the vehicle, each independently driven.

Prototypes 1, 2, 3, and 4 use the outer shaft for the high torque functions and the inner shaft for the high speed functions. Prototype 5 uses the inner shaft for the high torque functions and the outer shaft for the high speed functions. This change allows the outer high speed shafts on each side of the vehicle to be coupled together by a belt and driven by a single motor per side. This reduces the total motor count from 8 motors to 6. The lack of independent drive control of front and rear tracks on each side has not proven to be a large disadvantage.

7.2 Track Design

The tracks have evolved significantly over the course of several design iterations. The first functional prototype had tracks made from plastic conveyer links with rubber cleats attached. The tracks rode on two sprockets each, with the drive motor attaching via chain to the drive sprocket. The track beams had a single fixed attachment point, pivoting in the center. Each track beam was driven with an independent worm gear. At this point tracks were not field swappable without tools and considerable time.

Prototype 2 used timing belts for the tracks with the timing teeth on the outside functioning as tread. The tracks were perforated with a series of holes down the center, which engaged the sprocket teeth to keep the track aligned and to transmit drive torque. The track beams could be attached via a tool-less mechanism to the walk mechanism in the center or at either end so that configuration changes could be accomplished quickly in the field. The tracks rode on three sprockets of equal size. For any given mounting configuration, drive torque was transmitted to the one sprocket concentric with the walk mechanism axis. Because the track contacted the center sprocket only tangentially with no wrap, drive torque had to be transmitted from the center sprocket to the end sprockets using small idler gears when in the center mounted configuration.

Prototype 3 retained much of the same design, but added end sprockets smaller than the center sprocket. With non-equal sprockets, the track wrapped around a significant portion of the center sprocket on both sides of the track, so that drive torque was transmitted directly to the track. This eliminated the need for the idler gears. Prototype 3 also incorporated keyed attachment points on the tracks ensuring that the tracks would only attach in a single orientation per attachment point. This change simplified the software controlling the angular position of the track beams.

Prototypes 3, 4, and 5 all used timing belts with a variety of cleats attached to the outside. They also all used holes through the belt for alignment and torque transfer. Prototype 4 used the same track design as prototype 3 due to schedule issues. However, this was also partially due to the fact that the track design was converging and very robust at this point.

Prototype 5 used the inside timing belt teeth in addition to the holes for torque transfer. It had cleats with a rounded profile side to side, and a sharp profile front to back. This improved skid steering performance without sacrificing drive traction. Prototype 5 also included a refined track beam connect / disconnect interface replacing the old push-ring method with a simpler recessed push button design.

7.3 Body design

Each prototype has had a rigid body design except 3, which incorporated flexible joints between each of three body sections. This design allowed all the tracks to maintain contact with the ground over uneven terrain. This body configuration adds mobility in some circumstances, but adds weight and complexity and reduces body volume available for electronics and payload. For these reasons the flexible body has been shelved in favor of a unibody design.

7.4 Batteries and Power

Prototypes 1 and 2 used internal batteries that required the case cover to be removed for recharge or replacement. To rectify this design flaw, prototype 3 included two external battery bays allowing the rapid change of batteries without having to remove the electronics cover. Prototype 3 used a standard battery form factor widely used by the military. However, this battery did not prove to have the necessary power density to satisfy customer requirements. Prototypes 4 and 5 have a larger single battery bay rather than the smaller dual battery bays used previously to accommodate a larger and more commercially available battery with a higher power density.

7.5 Payloads

Although payloads were a consideration from the very beginning, prototype 3 was the first version of the Chaos robot to include a functional payload bay. The payload bay provides waterproof power, Ethernet, and serial connectors. This feature allows JAUS compliant payloads to be developed and easily integrated with the vehicle. Prototypes 4 and 5 also included a payload bay similar to prototype 3 for expandability.

8. SOFTWARE & BEHAVIORS

All software developed for the Chaos prototype conforms to the Joint Architecture for Unmanned Systems (JAUS) reference architecture 3.2. This provides a firm basis for the evolution and continued development of the Chaos software. The software systems that control the vehicle consist of two systems: the Operator Control Unit (OCU) and the Vehicle Control Unit (VCU). Both sets of software are based on existing Autonomous Solutions software developed for our commercial and military customers. Utilizing this software we were able to jump start development and work from a familiar code base to add the necessary features to the Chaos SUGV in a relatively short amount of time.

Advanced intrinsic mobility mechanisms and running gear, by themselves, are not sufficient to produce fluid SUGV mobility. They must be combined with operator assist algorithms and programmed behaviors to remain stable, cross obstacles, extricate from untenable situations, and to perform complex agility maneuvers. These behaviors are needed to realize the enhanced mobility potential of the Chaos designs.

8.1 Operator assisted tele-operation

One of the many challenges in designing a vehicle as complex and mobile as Chaos is making it simple for an operator to use. This challenge increases as the number of running gear and mobility options increases. Allowing an operator to control a skid steer vehicle in the same manner as a wheeled or legged vehicle requires intelligent operator assist algorithms. These algorithms must be transparent to the operator and provide predictive and consistent behavior. If the algorithms fail to accomplish any of these goals, the operator can become confused and frustrated. In designing the motion behaviors for the SUGV we have strived to keep the operator controls simple. To this end, a simple two joystick mapping was decided upon early in the development cycles. Figure 17 shows the joystick mapping for the chaos vehicle. (The left and right side motors are mounted 180 degrees apart, hence the motor command sign swap.)

User Action	Left Track	Right Track	Vehicle Motion
User pushes forward on joystick 1	T +	T -	Vehicle drives forward
User pushes reverse on joystick 1	T -	T +	Vehicle drives in reverse
User pushes left on joystick 1	T -	T -	Vehicle turns left
User pushes right on joystick 1	T +	T +	Vehicle turns right
User pushes forward on joystick 2	B +	B -	Vehicle walks forward
User pushes reverse on joystick 2	B -	B +	Vehicle walks in reverse
User pushes left on joystick 2	B -	B -	Vehicle walks left
User pushes right on joystick 2	B +	B +	Vehicle walks right
T = track B = beam			

Figure 17 - Chaos Joystick to Motion Mapping

8.2 Adaptive Gait / Walking Styles

Another feature of the Chaos operator control system is the ability to dynamically adjust track beam angle and speed to match a walking style or gait. The operator can easily change gaits by pressing a button on the joystick. Obstacles such as curbs, steps or rubble-strewn terrain, are best traversed in walking mode or by combining walking mode with rotating the track. The walking mode enables the robot to step up onto the object (rather than bump into it). Due to the long moment arm, walking mode is not capable of exerting large force at the end of the leg. But rotating the track provides high force. Combining the two enables the vehicle to climb stairs and obstacles.

8.2.1 Stair / Obstacle Approach

The stair / obstacle approach begins with the front track beams of the vehicle rotated to match the obstacle angle and the back track beams flat on the ground. As the vehicle is driven forward, the front tracks are better able to grab the lip of the first stair and get initial traction. As the vehicle continues to drive forward and climb the stairs, the front track beams are rotated downwards towards the level position to increase traction. At this point the vehicle continues to climb the stairs as it would a standard slope (tracks flat).

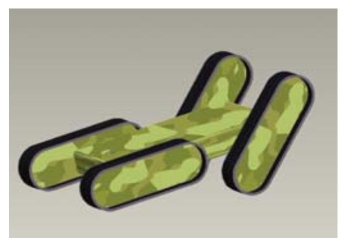

Figure 18 - Stair / Obstacle Approach

8.2.2 Inch Worm (Sea Serpent) Gait

The inch worm gait allows the vehicle to walk in a front to back undulating motion. For this gait both front track beams begin at the same angle while both rear track beams are set at 90 degrees to the angle of the front beams. Track beam speed / position is then controlled such that when the front track beams lift the front of the vehicle to its highest point that the rear track beams are flat keeping the rear of the vehicle at its lowest point. This results in a motion similar to an earth worm or sea serpent.

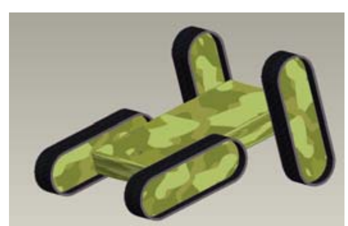

Figure 19 - Inch Worm Gait

8.2.3 Waddling Duck Gait

The waddling duck gait allows the vehicle to walk in a side to side waddling motion. For this gait both left track beams begin at the same angle while both right track beams are set at 90 degrees to the angle of the left beams. Track beam speed / position is then controlled such that when the left track beams lift the left side of the vehicle to its highest point that the right track beams are flat keeping the right side of the vehicle at its lowest point. This results in a motion similar to a waddling duck.

Figure 20 - Waddling Duck Gait

8.2.4 Paddle Wheel (Flailing) Gait

The paddle wheel gait allows the vehicle to walk in a staggered step motion. For this gait the left front track beam and the right rear track beam begin at the same angle. The right front track beam and left rear track beam also begin at the same angle relative to each other, but at a 90 degree angle from the other track beams. Track beam speed / position is then controlled such that each track beam remains in sequence with the track beam diagonal to it. This results in a motion similar to a paddling wheel.

Figure 21 - Paddle Wheel Gait

8.2.5 Self Leveling / Trajectory Tracking

Using feedback from roll and pitch sensors it is possible to dynamically adjust track beam angles to effectively provide self-leveling of the vehicle chassis. This capability can enhance platform stability on slopes or in rough terrain. In addition, feedback from a yaw sensor can be used to provide trajectory tracking. This feature allows the vehicle to follow a commanded trajectory (e.g. straight forward) despite hindrance from obstacles, slippage, or other factors. Trajectory tracking is accomplished by modulating or augmenting track and beam speeds to keep the vehicle on course.

8.3 Semi-Autonomous Obstacle Characterization / Traversal & Extrication

In addition to pre-programmed behaviors, Chaos is currently being outfitted for semi-autonomous operation. Using sensor feedback Chaos will be able to detect obstacles and utilize appropriate behaviors to overcome them or extract itself as necessary.

9. CONCLUSION

Chaos is a SUGV with the capability of utilizing a wide variety of running gear including: wheels, tracks, legs, and articulated / shape-shifting tracks. The vehicle offers unprecedented mobility including: walking, stair climbing, clambering over obstacles, and steep slope traversal. To fully exploit the vehicle’s mobility, intelligent behaviors have been developed that also reduce the complexity of vehicle operation. Mobility behaviors include: operator assisted tele-operation, adaptive gaits, and obstacle detection, traversal and extrication. Chaos is still under development, but very soon it will be able to perform important military physical security and homeland defense functions.