Less is More:
AURORA - an example of minimalist design for tracked locomotion

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I. ABSTRACT

Much work by many researchers and developers [1][2][6] over the last century has developed a vast body of knowledge in the areas of locomotion utilizing wheels, legs, tracks, etc. for applications from research to real-world applications. This paper addresses a novel development of a steerable monotread, dubbed ***AURORA*** (***A***dvanced ***U***rban ***RO***bot for **R**econnaissance and **A**ssessment), proving that a single continuous belt, designed with key flexure and guide-elements, is capable of steerable locomotion. This is believed to be a significant departure form the theory that tracked vehicles need to have at least two treads to steer. The system was built with a flexible elastomeric monobelt with a central drive- and guide-spine, which when flexed, forces the tread into a shape allowing it to steer. The system is also capable of inverted operations, stair-climbing (with the help of a deployable ramp/paddle), and easily portable due to its small size and low weight. The system is battery-driven and controlled/monitored over a wireless link, allowing it to be deployed safely into hazardous and remote areas in urban terrain. On-board cameras provide multiple side- and bird's-eye views, with on-board computing processing and interpreting imagery. A portable control-box is used for remote control. Preliminary tests have shown the capability of the system to handle rough terrain and steer in all of the environments tested so far. Future work will extend the autonomy capabilities of the system and ruggedize the tread and drive/steer elements even further.

II. INTRODUCTION

The use of the most adept locomotion mode(s) for natural/man-made environments represents an essential element of any mobile machine or robot system. Depending on the type of environments to be encountered, different locomotion modes are used to satisfy many requirements such as accessability, terrainability, speed and stability, etc. In the case of tracked vehicles, which are typically used in marginal (low contact-pressure) environments, designs have typically focussed on dual-tread systems, which are steerable in a differential-drive mode resulting in skid-steering locomotion - numerous examples exist in the literature [3]. Recently, commercial and military developments have led to the miniaturization of these systems into more 'suitcase-sized' devices, with the aim of becoming portable/luggable by an individual in such applications as anti-terrorism, EOD and military reconnaissance. Some examples from companies offering these systems for sale [4], are shown in Figure 1,

Figure 1 : Smaller-scale tracked/wheeled commercial 'field-worthy' locomotors

with other numerous examples also found in the research literature[2][8][9]. The main attribute of all these systems is their usage of parallel locomotor-modules, whether they be wheels, tracks, legs, hybrids, etc. - the notion of symmetry seems paramount in terms of stability and traction/steering. Very few robot-designs have 'violated' this seeming trend, with hopping and 'slithering/crawling' robots being an obvious exception.

It is the contention of the author, that in order to provide for a smaller, lighter and more minimal and thus more portable design, that a single steerable tread is a possible answer for rough and marginal terrain.

III. BACKGROUND

The notion of a single tread being used for locomotion over rugged terrain with low contact- and shear-resistance, is not necessarily a novel idea. Developments dating all the way back to the 1970s and even before WW II, show that this idea had already been considered. The first evaluations of these types of locomotors were carried out mostly by the US Army, especially for use in arctic and marshy terrains for transporting light-cargo and personnel. Some of the main systems in this category are shown in Figure 2:

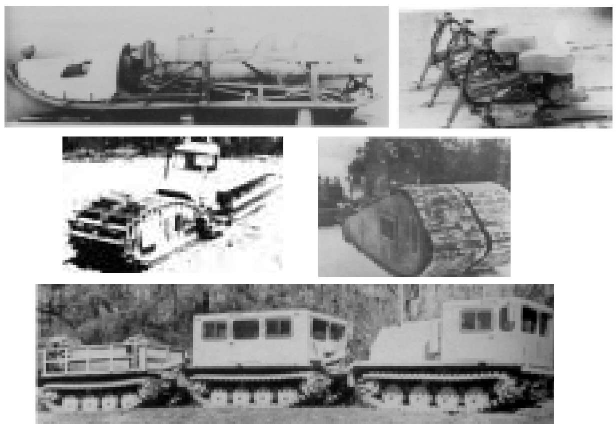

Figure 2 : Early single-track locomotors tested by the US Army

Note that steering systems for these ranged from front-mounted skis (predecessors to snowmobiles), to compact dual-tread arrangements with internal drives, to in-line dual-tracked carriers with hinged (both passive and active) joint-connections.

More recently (last 20 years), inventors have patented a wide variety of single-track steerable slat-based tracks with involved linkage-steering and segmented and interconnected tread-sections - a few of the main images from these patents are depicted in Figure 3:

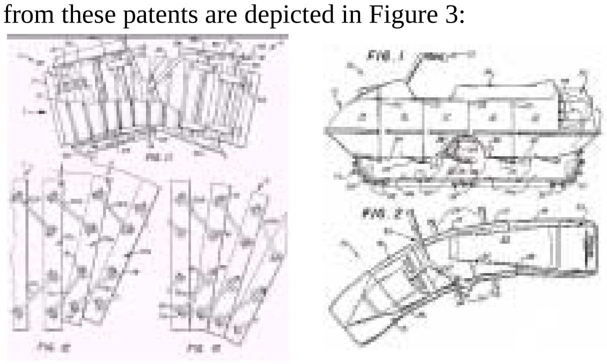

Figure 3 :Patented articulated segmented drive-treads

Over the last 5 years, developers and inventors have taken miniaturization and extreme locomotion-capability in single-tracked vehicles to another level, by developing in-line arrangements of these locomotors, and using them to crawl into areas through restricted passages, such as pipes, etc. - a sampling of such system-designs is shown in Figure 4:

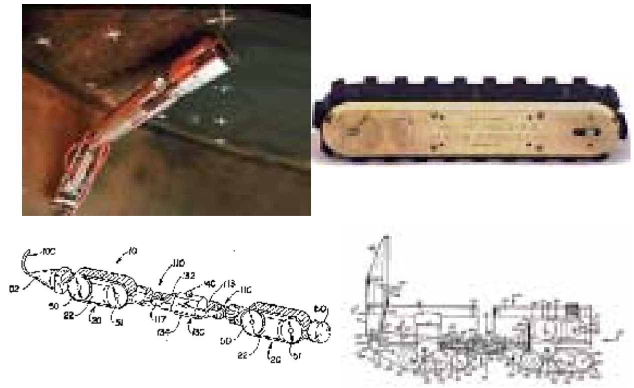

Figure 4 : Newer in-line tracked designs/concepts

Another area of industry that uses continuous moving surfaces is the materials-handling sector. They have been using continuous belted-/slatted-/roller-conveyors for decades, and have found particular usage for space-saving fixed-configuration curved conveyors in warehousing and E-commerce distribution and logistics areas. The only design that has been capable of providing for both straight and curved orientations in a single non-interrupted run is that of the slatted-conveyor system - a few demonstrative examples for these systems are shown in Figure 5:

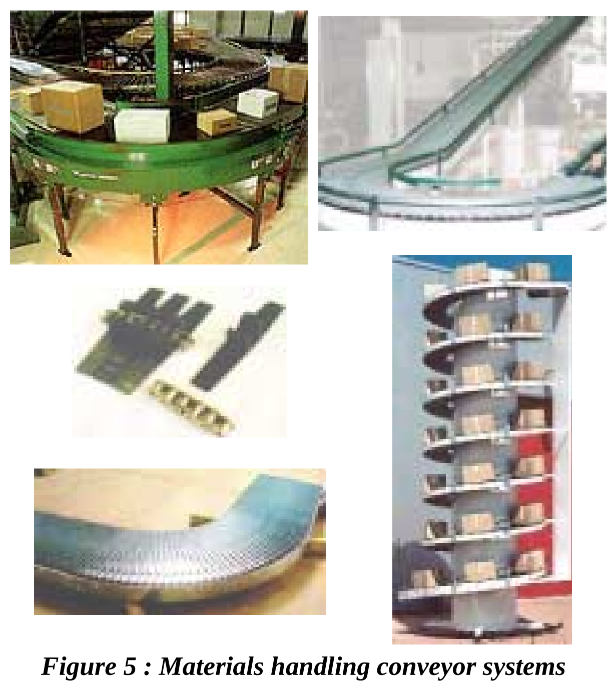

Figure 5 : Materials handling conveyor systems

In evaluating all this prior art, one can notice that outdoor steerable slatted-conveyors do not seem reliable enough, yet indoors they seem very feasible and usable. Continuously-belted single-treads (dual-systems exist) and conveyors have to date not been made steerable to our knowledge, yet they offer major advantages for outdoor rough-terrain locomotion, as do dynamically-steerable indoor slatted conveyor systems. It is proposed herein that AURORA is capable of filling these untapped niches.

IV. PERFORMANCE REQUIREMENTS

The need for this specification was driven by the desire to rapidly, economically and manually be able to deploy capable remote-controlled robots into hazardous areas, such as disaster zones, earthquake-damaged buildings, terrorist/hostage situations, bomb-threat scenarios, military urban reconnaissance, etc.

The original concept that was developed as part of the design-development phase of the program, centered on a device with as many commercially-off-the-shelf (COTS) components as possible, including a steerable conveyor-segment chain steered through linear actuators, and including on-board power, communications and drive-actuation. An artist-rendering is shown in Figure 6.

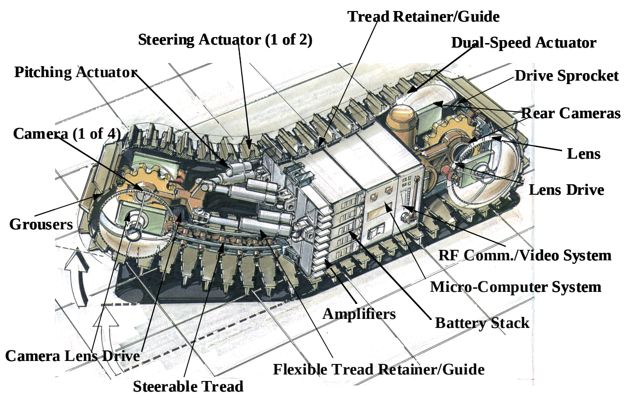

Figure 6 : Artist rendering of steerable monotread

In order to refine and evaluate this and other proposed concepts, a set of performance requirements were developed, describing the key attributes that the system should meet (a more appropriate label might be desirements) - they are detailed in Table 1 below.

The performance requirements that were developed for the proposed locomotion system, focussed around several key areas, namely (i) size and weight, (ii) terrainability, (iii) environmental hardening, (iv) mission-duration, (v) sensor payloads, and (vi) usable teleoperatable range. The key ones the development chose to emphasize, were (i) and (v), without compromising (ii) and (iii), while maximizing (iv) and (vi). This philosophy then led to the final design and prototype detailed in the next section.

V. SYSTEM DESCRIPTION

The design developed for the steerable monotread system was driven by the above-described design-mantra, and resulted in an extremely compact computer-controllable untethered locomotion system. The component-design challenge in this concept lay in the ability to develop a controllable flex-structure to shape, guide and retain a new type of laterally-compliant, yet longitudinally rigid flexbelt. The integration-challenge lay in providing for the driving and steering actuation in a compact package capable of meeting the performance requirements as specified in Table 1, while also providing for substantial on-board computing and communications power, and all of it capable of untethered operation through high-density chemical-cells.

The main feature of the system is thus clearly its steerable track and guide system, as well as the miniaturization of the drive- and steer-components to fit into the small-scale package desired by the sponsor. On-board sensing and computing was based on COTS components, as was the communication-links built into the system. Battery-power was provided through a set of rechargeable metal-hydride and lithium-ion packs custom-built for this system. An overall image of the design developed as part of this program, is shown in Figure 7, with a more detailed treatise to follow.

DESCRIPTOR	TARGET	VALUE
Size	*As small as possible*	***24"L x 6"W x 6"H***
Weight	*As light as possible; man-packable*	***$\leq$ 20 lbs.***
Speed Capabilities	*Flat floor and climbing*	***< 2m/sec. flat; 0.5 m/sec. on 60^o slope***
Terrain Types	*Capable of handling: Sand, Grass, Rubble*	-
Device Features	*Self-righting, stair-climb*	-
Turning Radius	*Minimize swept arcs*	***18" Radius turn***
Environments	*Specifications of temperature and humidity*	***-10^{o}C - 65^{o}C; 3' UW***
Shock	*Handling and driving w/o damage*	***drop-heights: 8'/3' on grass/asphalt***
Mission Duration	*Driving at top performance-level*	***1 hr. at full speed; 3 miles+ range***
Communications	*Usable real-time link range*	***1 - 3 miles outdoors; 300+ yds. indoors***
Interface	*User Control Devices*	***Laptop, Monitor & Joystick control***
Sensing	*Proprioceptive on-board devices*	***Color camera(s), Microphone(s)***

Table 1: Performance Requirements

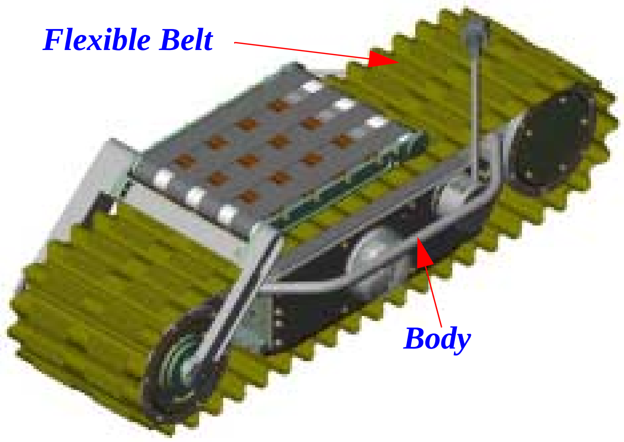

Figure 7 : Assembly design for AURORA

OVERALL SYSTEM: The overall assembly design shown in Figure 7, shows the tread in a straight configuration, including the front- and rear drive and posture hubs, the central enclosure, cameras and the deployable paddle, which allows the system to self-right itself, and climb onto obstacles taller than its own half-height. If the tread were to be removed, the central elements of the system can be exploded to show the design, as depicted in Figure 8:

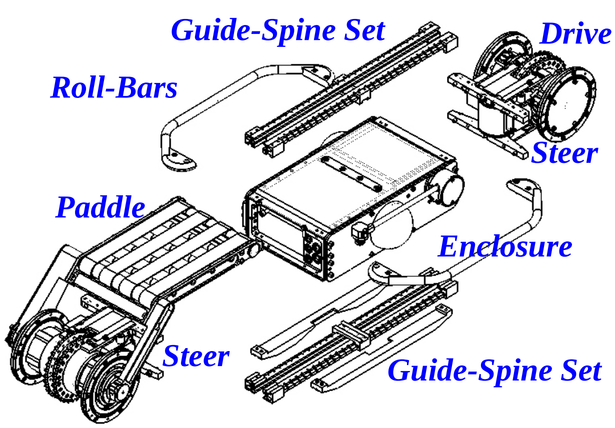

Figure 8 : Exploded view of drive- and structural systems elements

TREAD: The frame system in its most simple form, consists of the continuous belt, the drive-spine attached to it, and the guide-spines, which when deflected will bow the belt and retain the bent shape, thereby enacting a turning motion (see Figure 9 for the basic element design).

Different continuous-belt designs were explored in terms of their grouser- and webbing-arrangement, including typical slatted conveyor-sections, plastic grousers with intermediate webbing, as well as continuously-cast urethane webbed-grouser designs. The latter approach proved to be the most rugged, reliable and straightforward to manufacture. The prototyping method utilized is based on developing an SLA-positive of a tread-section, developing a silicon-mold and pouring a urethane section. Several sections if glued together would result in a continuous belt, with the required curvature-capability as shown in Figure 10:

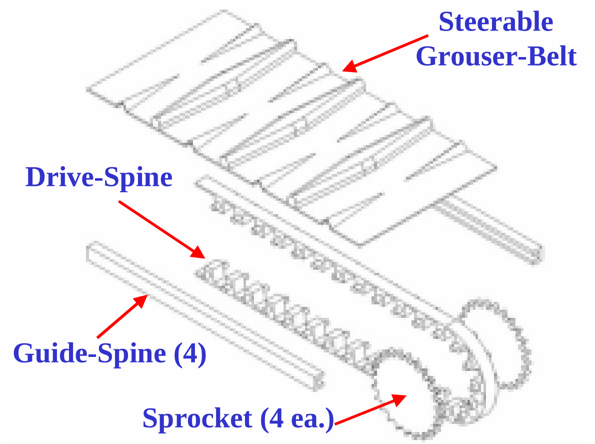

Figure 9 : Basic tread-elements

Figure 10 : Steerable monotread design & parts

The drive-spine, which is glued to the inside-curf on the continuous belt, is made from a custom-molded medium-durometer urethane, into which are embedded Kevlar backbone-fibers, as well as a set of drive-pins with low-friction ends to assure proper engagement with the drive-sprockets and low-friction passage within the guide-spine(s) - see Figure 11 for an up-close piece-parts view:

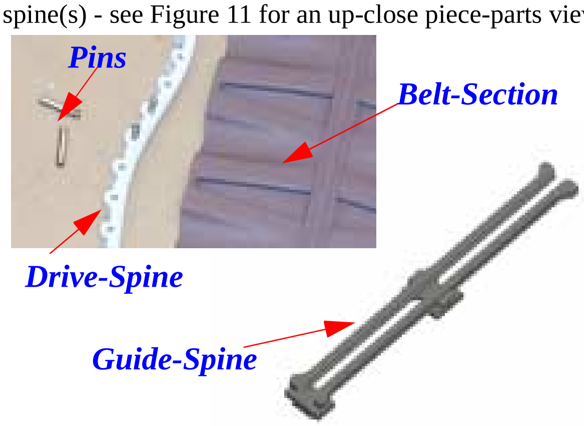

Figure 11 : Drive- and guide-spine details

DRIVE & STEER: The continuous tread is driven at the end of the assembly by a multi-stage planetary gearbox, driven by a coaxially-mounted brushless motor. A set of clutch and brakes internal to the assembly, allow the gearbox to change ratios, thereby giving the system a low- and high-speed capability - this was the only feasible approach to simultaneously satisfy the high-speed and high-torque climbing requirements. An image of the assembled and cross-section of the drive-section, are shown in Figure 12:

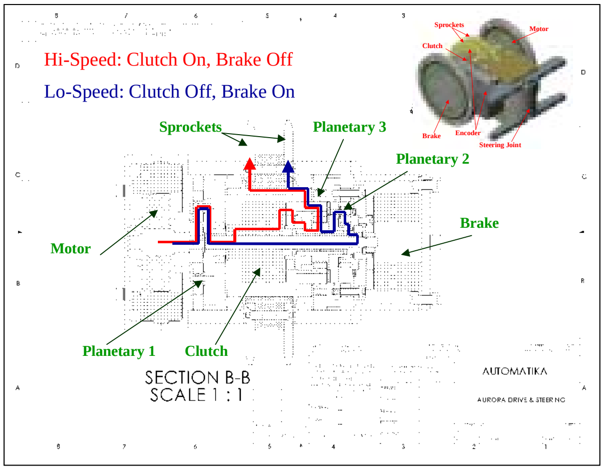

Figure 12 : Monobelt drive actuator system

The AURORA system uses two separate steering motors in order to steer the tread - one on each end offset longitudinally from the cylindrical end-sections. The steering is achieved by a stepper motor, geared through a helical gear-set, driving each cylindrical end-section to a +/-30^{o} angle, achieving thus a net 60^{o} steering-curvature angle. An image of the steering actuator is shown in Figure 13:

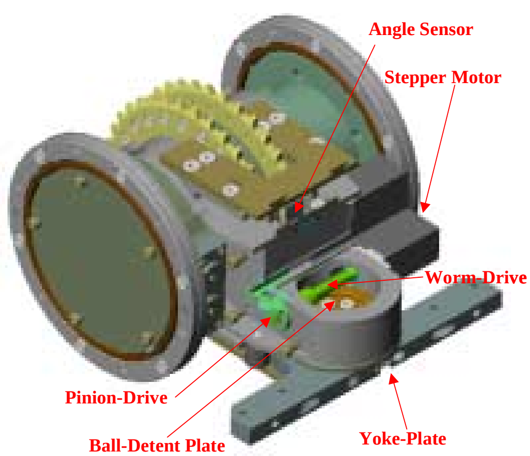

Figure 13 : Monotread steering actuator system

STRUCTURAL HOUSING: The design for AURORA utilizes the *mono-coque* method, by which the structural support and strength of the system is provided through the environmental-enclosure. The enclosure is made of a custom-laid carbon-fiber epoxy rectangle, with embedded frame-elements for the enclosure 'lids' and the battery-compartment separator. The batteries are accessible through a separate cover in the lid, while the electronics (computing, navigation, communications, custom PCBs) are shock-mounted and heat-sunk to endplates bolted to the end-sections of the enclosure. An exploded view of this assembly is shown in Figure 14:

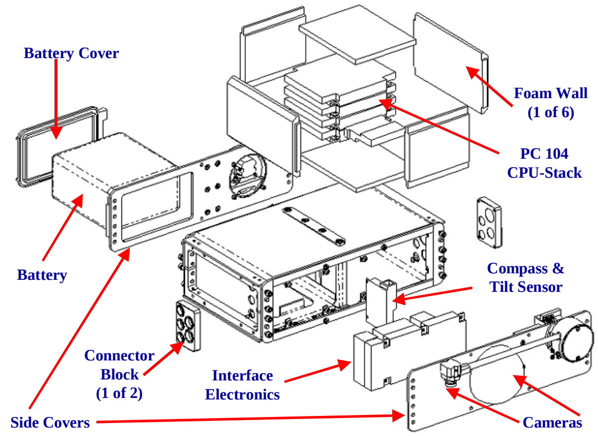

Figure 14 : Enclosure and internals view

ELECTRONICS: The overall electronics architecture for the AURORA system is based on a simple PC-104 Pentium-based computer-stack, which interfaces to all peripherals. Communications and control of all on-board devices is achieved over a dedicated parallel I/O card, which interfaces to a custom-built PCB to drive all the motors (PWM & Steps), control all the cameras (pan/tilt servos) and signal-switching, while also processing the navigational-attitude data-stream (roll/pitch/yaw with magnetic compass-heading). All video is frame-grabbed and digitized for transmission with all status and update data over the wireless ethernet link using standard WaveLAN 2.4GHz PC-card solutions. The power-pack is controlled and monitored for voltage and (dis-)charge rates at all times. A simplified version of the implemented architecture is depicted in Figure 15:

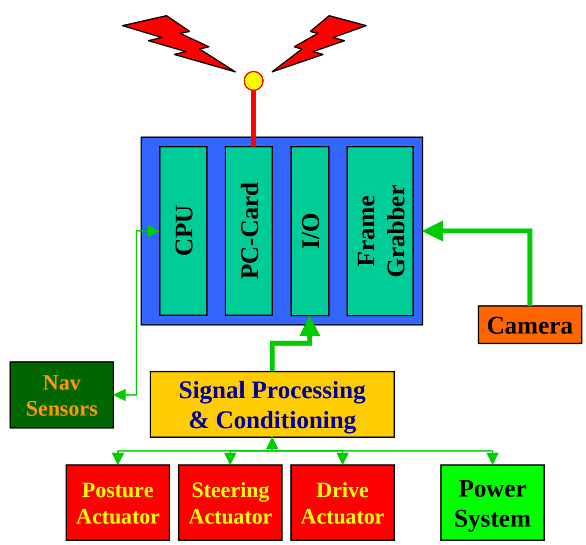

Figure 15 : Electronics architecture diagram

SOFTWARE: The main control-mode for AURORA is through teleoperation over the wireless LAN-link, utilizing a separate analog video- & audio-transmitter channel provided over a separate non-interfering frequency. However, there are several on-board autonomous or self-guarding algorithms that are intended to protect the system itself.

These algorithms are simple interrupt-driven semaphore-based loops that monitor key variables. Hardware-protection is enabled by monitoring temperatures and currents, in conjunction with pitch, to allow the system to automatically switch gears (down or up) to reduce the load on the motor and achieve as high a speed as possible without overheating the motor, electronics and battery-pack. A posture-guarding algorithm monitors the navigation-sensor to ensure that the system is not operating on too steep a hill or slope. The system simply warns the user, without interrupting operation, as it can roll over and tumble and either self-right itself or continue operating inverted (operator-choice). Comm-reestablishment is based on the statistical data provided through the wireless ethernet-based control-link, allowing the system to determine link-integrity. If link-integrity is poor or packet-loss excessive, the system will automatically stop and retrace a backwards-played script of commands for a period of up to a minute, while continually monitoring the link-quality, before returning control back to the (tele-)operator.

EXTERNAL SENSING: The main sensory device(s) for the AURORA system are based on visual and audible feedback. Due to the systems' low-to-the-ground design, its need to operate in confined spaces or in stealthy modes, and the packaging-requirement of minimizing protruding parts, the design developed into a three-camera arrangement. Two cameras are mounted inside of Lexan-spheres which are mounted to the side-covers of the enclosure - each of them sits on a panning miniature RC-servo controlled via PWM. The third camera is mounted atop a deployable flexible stalk (to avoid damage during flip-over if deployed), which has a rotational-joint within the enclosure to raise/lower the stalk, while a panning actuator turn the entire stalk, thereby creating a panning-motion of the camera. All cameras are miniature CMOS-based single-board color cameras, encapsulated into silicone for environmental sealing. No external lighting has yet been provided for, but discussions about adding low-power high-intensity 'white' LED light-rings is being considered for a future version. The individual assemblies for both the side-dome and stalk-cameras, are depicted in Figure 16.

SYSTEM ASSEMBLY: A fully assembled pre-prototype locomotion platform had been built to test the tread-designs, and to allow teleoperation evaluation/training of operators via built-in RC-servos and standard radio-control interfaces. The pre-prototype that was built and tested is shown in Figure 17:

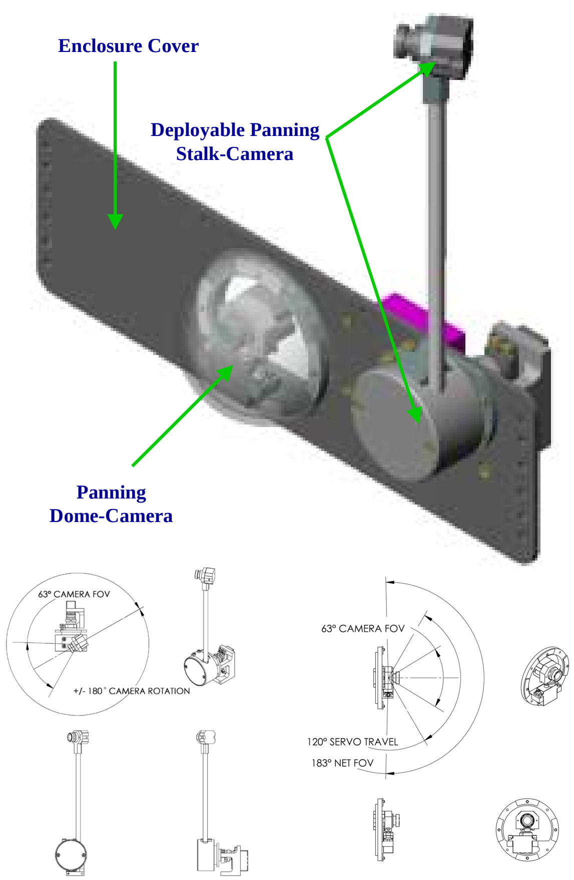

Figure 16 : External video camera sensors

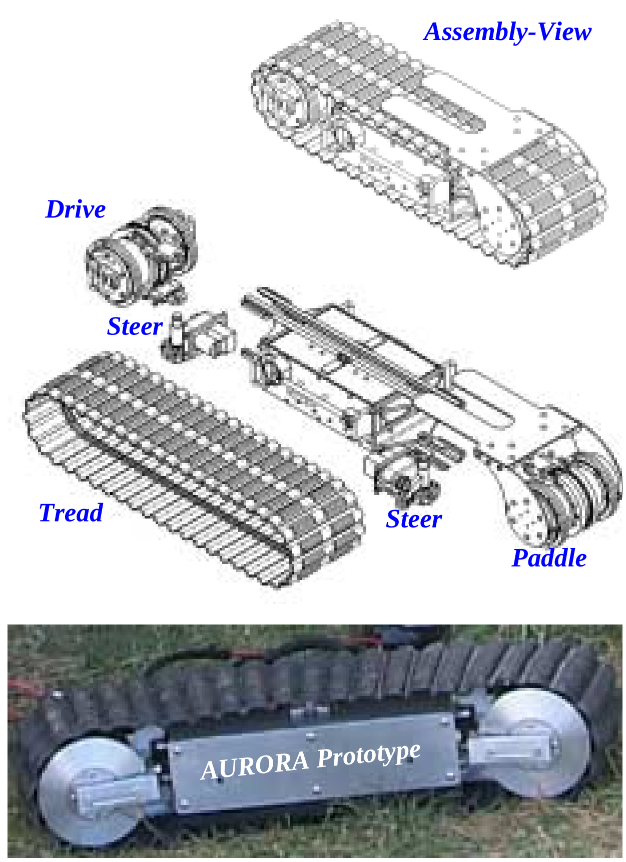

Figure 17 : RC tread-test platform - CAD and as-built

VI. PROTOTYPE TESTING

The computer-controllable AURORA system is currently undergoing assembly and testing, with an expected completion date of late-summer/early-fall 2001. In the meantime though, a pre-prototype had been built to not only test the tread-designs, but to also allow teleoperation training of operators via built-in RC-servos and standard radio-control interfaces. The pre-prototype that was built and tested is shown in Figure 18.

Figure 18 : AURORA test prototype

Initial functional testing indicates that frictional-losses due to the use of the captured steerable belt are fairly reasonable. Power-consumption of 110% over nominal no-belt idle speeds was measured, while steering-consumption jumped to 150% for the sharp 60^o turning radius at average speeds. The guide-spines were found to work surprisingly well, even becoming self-cleaning due to the drive-pins in the drive-spine keeping debris from the groove. The continuous belt systems' lack of pre-tension afforded by the complete capture of the belt, clearly impacted to high-efficiency steering of the system. The guide-spine material will have to be chosen carefully so as to maximize wear-life, without impacting power-draw excessively.

Figure 19 : Outdoor pre-prototype testing scenarios

The system was shown to be capable of climbing steep gravel slopes and drive through vegetative stands much taller than its own size (see Figure 19). Stair-climbing was also shown to work; two-point runs were necessary on very narrow (fire-escape-sized) stair-landings.

The final computer-controlled prototype is due to be assembled in May, and undergo functional and operational testing in July and August. A final demonstration to the sponsor is expected in late September 2001 under realistic urban reconnaissance field-conditions.

VII. SUMMARY & CONCLUSIONS

The monotread design and prototype system presented in this paper is believed to be novel and a departure from the typical tracked [3] locomotor system designs, as well as those considered hybrids [9] and extreme [8]. Its design represents a minimalist approach to rough-terrain tracked locomotion, and is believed to offer viable and beneficial alternatives to existing systems. The design for the tread wa proven to be possible, with an optimal tread- and flex-structure design presented herein. Integration of mission-relevant sensors, computing, communications and power systems was shown to be feasible in the required size-range. The choice of battery-chemistry clearly drives the weight-specification, with the final system exceeding its weight target by 15% (23 lbs.). Test-results indicate that the system s capable of outdoor rough terrain driving and steering, while also climbing stairs and achieving sufficient traction and flotation in sandy, wet and soft soil conditions.

VIII. FUTURE WORK

The system presented herein represents the first generation of steerable monotreads for use as remote-controlled and autonomous inspection and reconnaissance mobile platforms. The next-step in development will be the augmentation of system capabilities in the areas of sensor integration (microwave-radar, acoustic, etc.) and power-density (fuel-cell or other battery-chemistry) to enhance its mission-specific autonomy behaviors. Since the continuous belt is the main feature of the system, continued work will emphasize the selection of a proper combination of materials and durometers, and developing a single-step fabrication-method to reduce labor and prototyping costs. Alternate applications for this system design are also being explored in other completely unrelated commercial arenas.

IX. ACKNOWLEDGEMENTS

The steerable monobelt system development was funded at Automatika, Inc., by DARPA under research-grant #00-C-0655. We wish to further acknowledge the help from many other team members at Automatika, Inc. to develop

the tread and structure systems. The notion of a flip-up camera was proposed by M. Hebert at CMU, and we have thus dubbed the deployable stalk-camera the MartialCAM in his honour. The above-described AURORA system has been filed with the US and International Patent Offices under the PTC for patent-protection and has a patent-pending status.

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