Pandora: Autonomous Urban Robotic Reconnaissance System

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I. ABSTRACT

Urban settings represent a challenging environment for teleoperated and autonomous robot systems. We present a new design for a highly terrainable robot system, detailing the major mechanical, electrical and control systems. The Pandora robot system is a tracked robot system with self-contained computing, power and wireless communications systems. A sensor suite including stereoscopic and panospheric cameras, light-stripers and acoustic sonar-ring(s) allow the system to operate autonomously. Individually adjustable track-modules give Pandora extreme mobility in natural (vegetation, soils) and man-made (roads, steps) outdoor environments as well as indoor arenas (sewers, staircases, etc.). Locomotion was shown successfully over various extreme terrains, including reconfiguration to best suit the terrain and enable future sensor-supported autonomous operations.

II. INTRODUCTION

The need for robotic scouts, pointmen or recon-drones in urban settings, come from the facts that military operations in urban environments are highly dangerous, time-consuming and incur the largest percentage of casualties in modern engagements. The use of a robotic system with sufficient sensory capability to detect opposing elements, sufficient autonomy to not distract moving unit operators, and sufficient locomotion and power-autonomy to access any area over long-duration missions would be a great asset to the U.S. ground forces. Since these kinds of systems do not exist at this time, and their best mission profiles and capabilities have not been evaluated, it became important to establish a program at DARPA that would pursue the development and evaluation of prototype systems in realistic scenarios to better understand the utility of robotics in urban operations.

Current urban operations, based on our limited introduction and short exposure to a training mission at the MOUT training facility at Camp Pendleton in CA, can be termed highly intricate (see Figure 1). The goal is to advance through the urban setting, without exposing oneself in a lethal situation, thereby flushing opposing forces from strongholds in the setting, while securing the area for non-combatants and behind-the-lines operations. Typically this involves a three-man force advancing under any cover through the urban terrain, trying to detect any opposing forces in the large number of possible hiding places (sewers, roofs, doors, walls, etc.) so as to overwhelm or flush them out in the process of securing the urban setting a building/block/street/neighborhood at a time. The key during this operation is to get as much data to the team for them to evaluate the potential for threat, whether it is in the sewers, higher-up floors (snipers), behind walls/vehicles, etc. - the ability to gather and process reconnaissance data without exposing oneself in a potentially lethal manner is thus highly desirable. The remote reconnaissance system would at the same time need to be able to proceed over terrain amenable to humans, progress at a human-equivalent speed, carry capable sensors for reliable threat detection, and operate with a minimal of human supervision/guidance. Such a system should thus either seamlessly fit into the current mode of operation, or be excessively competent in other areas so as to allow the teams to utilize different tactics, which in turn will affect the dynamics of urban reconnaissance and assault operations.

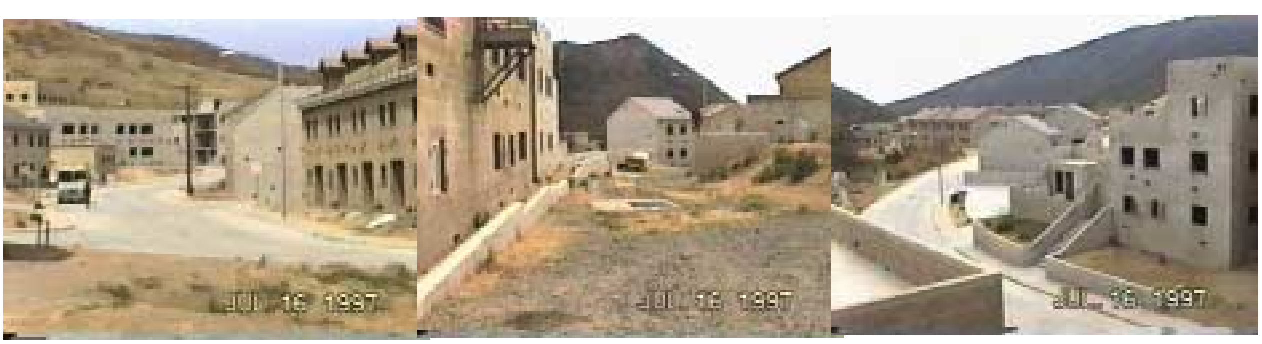


Figure 1 : Typical 'sanitized' urban settings for MOUT training camps destined for robotic reconnaissance

III. PERFORMANCE ENVELOPE

The conditions and situations (i.e. the problem description) that a robotic vehicle would have to deal with in such an urban environment can be described as:

- *Obstacle-strewn man-made cluttered environment*
- *Underground and High-up Danger-Zones*
- *Lack of friendly-cover and excessive foe-cover*
- *Run-and-stop cover-seeking mobility requirements*
- *Intelligence-gathering and coordinated attack strategy needs*
- *Multi-unit coordinated human/machine operations*

Based on these criteria, one can formulate a preliminary structured list of criteria that the robotic system design process will have to consider, such as:

- **Rugged Terrain**
  - *Obstacles - Steps, curbs and cinder-blocks*
  - *Ground - Asphalt, Mud, Grass, Gravel, Carpet, Concrete, etc.*
  - *Progress - Crawling to walk/run speed*
  - *Elements - Heat/Cold, Moisture/Rain, Dust, etc.*
- **Military Operations**
  - *Portability - Portable by infantry personnel*
  - *Mission-Duration - Typical 1 (continuous) to 4 (intermittent) hours*
  - *Multiple control and monitoring modes*
- **Low-interaction Interfacing**
  - *Non-intrusive minimal interaction interface*
- **System Ruggedness**
  - *Shock-proof, Curb-fall, Roll-over, Man-handle, etc.*

IV. SYSTEM OVERVIEW

The Pandora system design developed for urban operations, consists of a reconfigurable dual tread-driven skid-steered robot vehicle, which can orient its front- and rear pairs of tracks to allow it to climb up, -onto and -over a large variety of roads, curbs, bricks, boulders, steps, walls, ditches and through sewer-pipes (see Figure 2 & Figure 3).

Figure 2 : Pandora Pre-Prototype System

with a component layout for the final prototype-design as depicted in Figure 3.

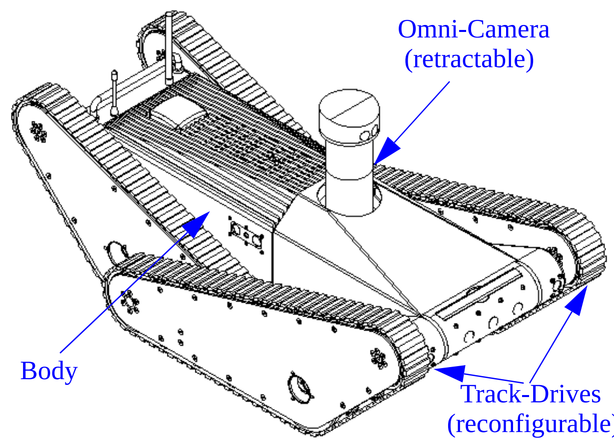


Figure 3 : CAD Rendering for prototype system

The system is capable of reconfiguring its treads into an infinite number of configurations, with some of the more useful ones depicted in Figure 4 on a mock-up of the platform (16” wide, 35” long, 10” tall).

Figure 4 : Pandora reconfiguration capabilities to deal with varied terrain scenarios

The internal architecture and component packaging for the Pandora system are depicted in Figure 5:

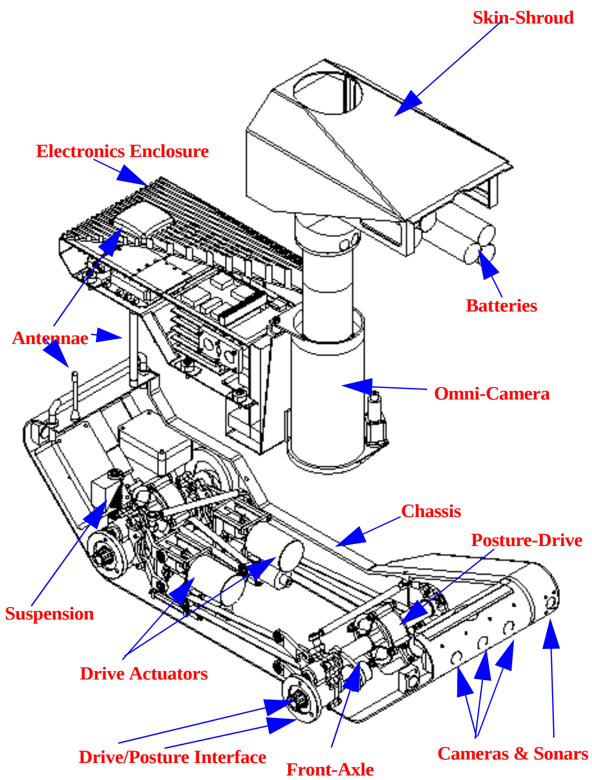


Figure 5 : Pandora's internal component packaging

The main systems within the Pandora vehicle system consist of the locomotor-modules (track-modules in this instantiation), the vehicle-chassis, the drivetrains, the electronics-enclosure, the omni-spherical camera, and the forward- and side-/rear-looking CCD-cameras and sonar systems.

Chassis: The chassis-system consists of machined-aluminum side-boxes with internal gusseting and penetrations for the axles, with a thermo-chemically and mechanically-sandwiched carbon-fiber-Kevlar chassis-pane. The system will be custom-made and have drainage and mounting holes for the drivetrain and enclosure hardware. Note that we do not intend to hermetically seal the chassis system, but rather use it as a structural and undercarriage element to contain and support all the robot's components. All chassis-internal systems will have to each be individually-sealable in order to withstand the elements.

Sensing Systems: The omnicamera (developed and provided by S. Nayar at Columbia Univ.) consists of a retractable see-thru cylinder, atop which sit a pair of laser light-strip projectors. The system is contained within an enlarged and sealed plastic cylinder, containing all the drive and actuation systems, mounted to the bottom-pan of the chassis. The forward-looking CCD stereo-pair is separately housed in a sealed enclosure, and then mounted to the front-end of the chassis, peering through two penetrations in the weldment. The separate infrared-filtered CCD-camera is mounted atop the stereo-pair in a slightly-bulbous weldment-area to clear internal drivetrain components and to provide the proper height above the ground and baseline between it and the light-stripers. The sonar system consists of a set of angularly mounted acoustic-transducers, a pair on each face (except top and bottom) of the robot, all wired into a multiplexer-unit.

Drivetrain & Suspension Systems: The drivetrain system mounts to the bottom-pane of the chassis, thereby locating the two-speed-transmission and thus locomotion drivetrain inside the vehicle. The front and rear axles are located by attaching the parallelogram linkage-arms of the suspension to the side-panes of the chassis, while attaching the stabilizer bars to the bottom-pane again. The axles are thus free to move vertically, and are constrained by a coil-spring elastomeric-bumper system at each axle-/hub-location to travel +/- 0.5 inches. The spring-tower is attached to the chassis bottom-pane, and is gusseted to absorb impact-loads into the chassis. The track-module, drivetrain system and suspension system arrangement, are depicted in Figure 6, Figure 7 and Figure 8, respectively.

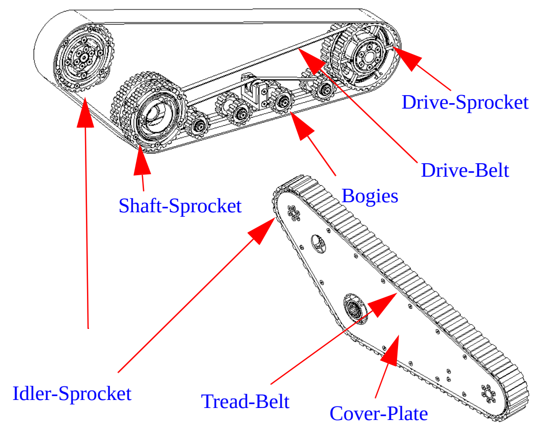


Figure 6 : Track-module system design

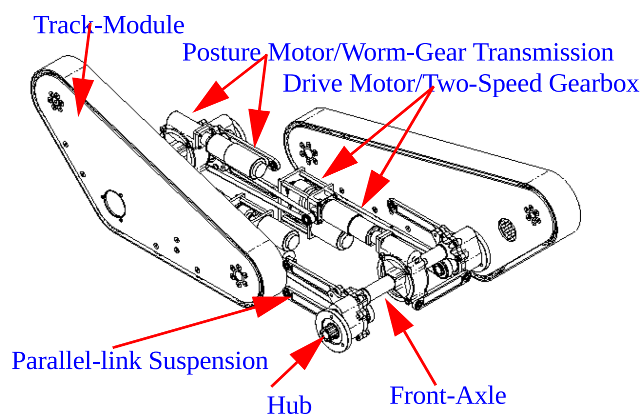


Figure 7 : Pandora drivetrain system

Electronics Enclosure:

The electronics enclosure is a stand-alone environmentally-sealed aluminum or sealed fiberglass 'weldment', which contains all the main electronics elements to run Pandora. The enclosure itself serves as a structural element in the rear of the vehicle, mounted to the chassis by way of elastomeric energy-absorbing elements. All components inside the enclosure are also shock-mounted via elastomeric spacers.

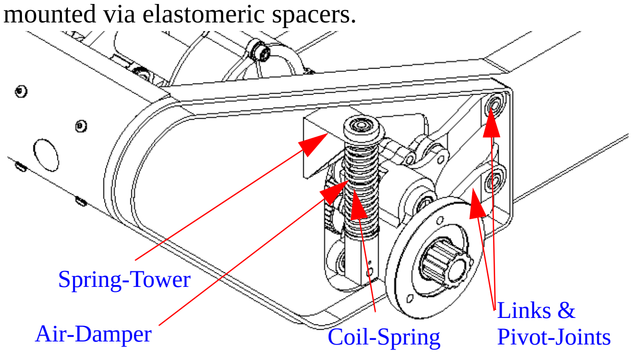


Figure 8 : Pandora suspension arrangement

The topside cover is made of a heat-sinking fin-extrusion, allowing the generated heat from all voltage-conversion equipment and the DC motor-amplifiers to radiate away from the vehicle. The main components within the enclosure and their packaging is evident from Figure 9:

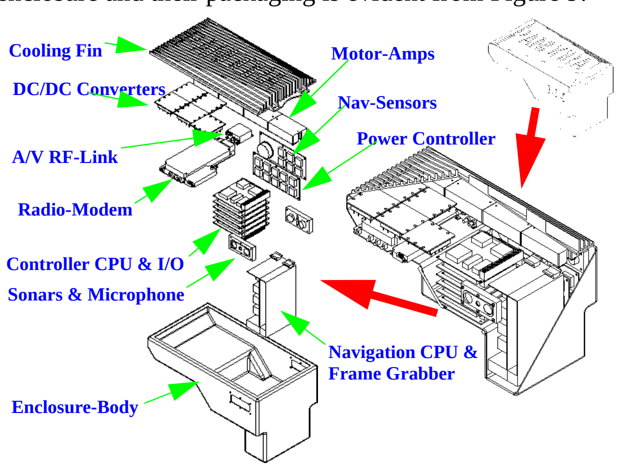


Figure 9 : Electronics enclosure packaging for Pandora

V. SYSTEM COMPONENTS

The component selection was based on thorough analysis of the performance requirements, resulting in the system specifications that had to be met. Component selections were critical in the areas of locomotion type and layout, computing systems, power sources and communications. Some of the more important findings of that effort for the Pandora system are described here.

- **Computing Architecture & Systems**

  The architecture that was selected was based on the use of a high-end Pentium-based navigation-CPU to perform the sensor-data gathering (video, light-stripe, sonar) and interpretation (modeling and autonomy behavior), with a second lower-power (X86 or 68HC11-based) vehicle-controller CPU to handle all the necessary vehicle control tasks. Control would be based on simple speed- and position-control for the drive- and posturing actuators respectively; integral motor-resolver and -encoder feedback was to be used. The processor was to continuously loop through the control structure, performing servoing of all axes, while servicing the navigation-CPU commands and feedback requests by way of interrupt service-routines. An on-board hardware and software heart-beat system was designed to ensure the safe operation of such an integrated computing system. Based on the availability of processors, and the desire of running a PC-based RTOS, in this case QNX, several candidate systems were identified (see Table 1),

Company	Model	CPU MHz	RAM Mb
RTD, Inc.	CMX486DX100	486-100	16
ADL	MicroSpace	486-100	16
Ampro	CoreModule	486-133	52

Table 1 : Pandora Vehicle-controller CPU: PC-104

and the Ampro selected based on higher RAM and clock-speed.

- **Power Consumption and Battery Selection**

  The power requirements for the system were split into two categories: continuous (sensors, computers, cameras, comm, quiescent, etc.) and intermittent (posturing, locomotion, brakes, encoders, etc.). Based on a careful component analysis, numerical analyses of power requirements based on realistic mission-scenarios, and a simple free-body diagram for slope-climbing and posturing (shown in Figure 10), including transmission ratios/efficiencies, as well as motor torque/speed curves and amplifier conversion efficiencies:

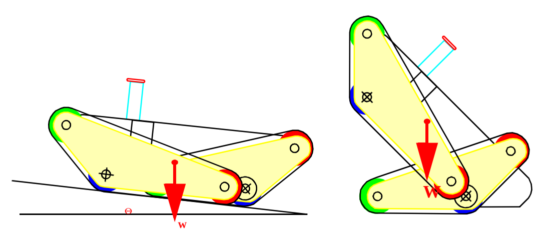


Figure 10 : Analytical free-body diagram

Pandora's power-consumption was thus computed for different slope angles, obstacle-sizes as well as reconfiguration motions, with the resulting summary-power levels as shown in Table 2:

Category	Power [W]	
	Typ.	Max.
Continuous	60	74
Intermittent	46	120
TOTAL	**106**	**194**

Table 2 : Pandora Power Breakdown

Based on the above power consumption, a suitable battery-pack (other options were explored but discarded due to the desire to integrate existing proven subsystems) had to be selected to provide the 1-hour continuous and 4-hour intermittent operation required. Battery technologies considered to be small-size, high energy- & power-dense where explored and are listed in Table 3.

Technology	Rechargeable ?	Nominal Voltage	Max Drain	A-hr	W-hr	Mass(g)	Vol(cc)	W-hr/g	W-hr/cc
Sealed Lead-Acid	Yes	12V	80.0A	6.5	78	2600	1000	0.03	0.08
Ni-Cd	Yes	8.4V	6.0A	1.4	12	280	265	0.04	0.04
LiNiCoO2	Yes	3.0V	2.0A	1.0	3.0	36	15	0.08	0.20
LiMnO2	Yes	2.4V	1.0A	0.75	1.8	17	8	0.10	0.23
LiMnO2	No	2.4V	2.5A	10.0	24	117	52	0.21	0.46
LiSO2	No	2.4V	4.0A	8.0	19.2	85	52	0.23	0.37

Table 3 : Battery technologies identified and used for selection

Based on Table 3, a set of $LiSO^2$ primary batteries from SAFT, Inc., which already supply battery-packs to the US Army, allowing us to retain conformity with tested and approved equipment. The battery-pack was made up of three ten-stack F-cells, resulting in a 24-Volt pack with the capacity to deliver 12A (maximum) over 1 hour (~12A-hrs) or 6A (typical) over three to four hours (~24A-hrs), as predicted by the drain-curves from SAFT (Figure 11).

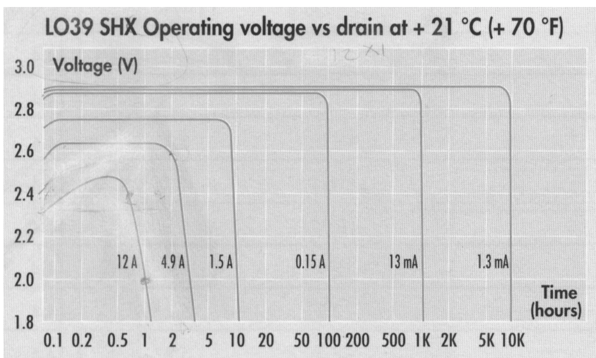


Figure 11 : SAFT LiSO2 F-cell drain curves

• **Wireless Data & Communications**

The requirement for live wireless video and bi-directional data-communications required the selection of a single-/multi-frequency RF-system. Due to the need to use off-the-shelf components and the differences in data-bandwidth, the decision was made to treat the video-system separately from the data-communications system.

In the area of wireless data-communications systems, we compared the wireless modems (Nomadic Technologies, Proxim, FreeWave) and LANs (Proxim, BreezeNet, Nomadic). We eventually settled on the FreeWave system (900 MHz, RS-232, 1.2 to 115 Kbps, 20 mile range with 1/2 mile in urban multi-path environment), due to its guaranteed transmission, -range and reliability properties we had proven in earlier uses.

The RF video-systems available today are fairly polarized in that they are either for 'hobby'-use (Supercircuits) or more professional applications (HDS). The former applies to amateur-spy applications where limited range, image quality and noise-immunity are not critical - they are however fairly cheap! The latter systems are split into commercially-available systems and/or government and military systems. We settled on a miniature 2.4GHz audio/video transmitter from HDS, Inc. with over a 1 mile range and proven multiple thru-wall 1/4 Watt transmission capability.

VI. FINAL SPECIFICATIONS

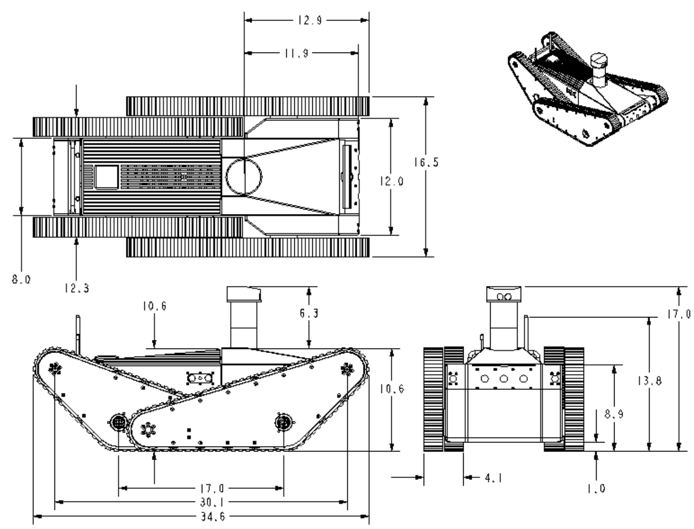
The final design of the Pandora system enables us to compile a list of system specifications for the final system, which allows potential users to gauge the utility of the design. Table 4 shows a complete listing of all the relevant system descriptors, with a terse description of their characteristics and numeric qualifiers (wherever possible/ applicable). The goal will be to compare the actual system performance once the system is implemented, and evaluate the soundness of the design at that time.

VII. OPERATIONAL SCENARIOS

The mission-scenario envisioned for the Pandora system depends on the ultimate usage of the system - we currently envision civilian as well as military applications. In the case of civilian application, the system will be transported by fire-crews or police SWAT-teams to a deployment site by way of a transport van, from where it will be deployed into a suspect or burning areas. On-board special-purpose sensors will be utilized to survey the area and detect potential survivors and/or explosives. Due to its small and reconfigurable size, the system will be able to travel over a vast variety of outdoor and indoor terrains and natural/ man-made structures/obstacles, in order to reach its target by way of teleoperation. In the case of a military application, the system will be carried to an urban setting from a transport vehicle, from where it will either be teleoperated or be driven autonomously with minimal supervision into different man-made structures (buildings, sewers, etc.) to performance reconnaissance for the advanced team - the goal is to determine the presence and location of civilian, friendly and enemy troops. Such information can then be used towards tactical advantage to avoid casualties on both sides, while gaining tactical and strategic advantage and securing target areas, buildings, etc.

In other special-purpose missions, the Pandora vehicle can be used as a mothership system, by carrying several smaller static/semi-mobile sensing systems with it, which it is told/programmed/instructed to drop at key locations. These individual sensing systems can be used to monitor via audio/video/etc. key locations/areas or even connected areas (assuming these sensors are able to achieve some

Category	Descriptor	Value	Range
Speed	Flat-/Incline-Driving	**5 mph**	**0 - 5 variable**
	Obstacle Climbing/Driving	**0.5 mph**	**0 - 0.5 variable**
Weight	Overall Estimate (pending further weight reduction)	**65 lbs**	**+/- 5 lbs.**
Size **(L x W x H)**	Collapsed:	**33”x16”x11”**	**+4”H (w. camera)**
	Straddling:	**33”x16”x26”**	**+4”H (w. camera)**
	Ditch-Crossing:	**33”x16”x15”**	**+4”H (w. camera)**
	Step-Climbing:	**46”x16”x11”**	**+4”H (w. camera)**
Environmental Conditions	Temperature	**20^{o}C**	**0^{o}C - 65^{o}C**
	Humidity	**45% RH**	**+55%/-45%**
	Immersion	**Waterproof**	**-> Watertight**



Category	Descriptor	Value	Range
Amplifiers	100 W PWM-cycle controlled pre-potted systems	-	**0 - 100 VDC**
Computing	Navigation Computer - P2/MMX Frame-Grabber: RGB & RS-170 Switcher	**233 MHz** -	- -
	Vehicle Controller - P2 Digital/Analog I/O Cards & CAN-bus	**166 MHz** -	- -
Power	Li-Ion Sulphur-Dioxide Primaries	**36V Assy.**	**1 hr. 1C Discharge**
Environment Sensors	OmniCamera with integral window/motion SW	**360^{o}FOV**	**-5^{o}Down**
	Forward-looking Stereo CCD-Cameras	-	-
	Filtered CCD camera with laser light-stripers	-	-
	4 x 2 vehicle-surrounding sonar-ring	**350 MHz**	**multiplexed**
Navigation Sensors	DGPS Trimble receiver	-	-
	Magnetic true-north Compass	-	-
	Gravity-compensated Inclinometers	**Pitch & Roll**	**+/- 80^{o}**
	Solid-State Gyro	-	**+/- 50^{o}/sec**
	Safety Switches: Mercury-bath binary camera-retract switch	-	-
Communications	2.4 GHz wireless RF-modem	**9.6 KBaud**	**bi-directional**
	Switchable Video/Audio Transmitter	**S-Band**	**transmit only**

Table 4 : Pandora System Specifications

small level of locomotion), relaying intelligence back to individual reconnaissance (military) or exploration (civilian) teams.

VIII. FIELD TRIALS

A functional pre-prototype system (teleoperated drivetrain and structural pre-prototype of Pandora without autonomy computing nor sensing) was rapid-prototyped and tested in a realistic urban ‘obstacle-course’ setting, by subjecting it to continuous reconfiguration posturing and obstacle-handling situations (Figure 12), step- and hill climb/ descent, and some initial operational scenarios in which an operator (shown in Figure 12 as a camouflaged engineer for effect) operates the system in outdoor and indoor scenarios to evaluate the system’s reconnaissance capabilities. It was determined that the ability to travel fast, topple over and recuperate (self-righting) or driving upside-down were essential.

Figure 12 : Pandora posture and deployment testing

The user-interface for the operator was found to be the most important element in need of much more design - the criteria of minimal and intuitive interactions are essential if such a recon-system is to ever find applications in such scenarios. From the myriad numbers of postures possible, it was determined that only about 5 are really essential and capable of handling 95% of all the terrains and obstacles we tested. The weight of the system needs to decrease from the current 65 pounds as well. The transportability of the system and the need for autonomy still require further investigation (not part of the funded work), leading one to consider the development of a much smaller and lighter teleoperated platform (no on-board sensing nor computing, akin to the toy-car/-plane systems) - the pros and cons between these two types of approaches are well worth investigating in our opinion.

IX. ACKNOWLEDGEMENTS

This project was funded by the Defense Advanced Research Project Agency (DARPA) under Contract Nº DAAL01-97-K-0165, in collaboration with Columbia University. We wish to further acknowledge the contributions of Martial Hebert (sensing and autonomy), Chuck Thorpe (user interfaces and operations) and Anthony Stentz (planning) as well as other team-members for their valuable insight and contributions to the final system design. Other organizations competing as part of this DARPA-funded work included IS Robotics, Inc., SRI, ARL and JPL. Patenting of Pandora is pending.

X. FURTHER DEVELOPMENTS

CMU and a commercial venture are continuing the development of the Pandora system into a smaller, radio-controlled teleoperated system, which is intended to be commercialized as part of a military, urban-rescue and entertainment system. In addition, the same partners are also continuing work on portable/wearable miniaturized control and display interfaces. We expect to report on such systems in late 1999.

XI. REFERENCES

[1] Schempf et. al, “Pandora - Design of an Urban Robot System”, CMU RI Tech-Report, to be submitted, Winter 1998.

[2] US Army Research Laboratories, “Pandora: A Robotic System for Operations in Urban Environments - Final Design Document”, official contract-report submission, March 1998.