

# Segway Robotic Mobility Platform

Hoa G. Nguyen,<sup>a\*</sup> John Morrell,<sup>b</sup> Katherine Mullens,<sup>a</sup> Aaron Burmeister,<sup>a</sup>  
Susan Miles,<sup>c</sup> Nathan Farrington,<sup>a</sup> Kari Thomas,<sup>d</sup> and Douglas W. Gage<sup>e</sup>

<sup>a</sup> SPAWAR Systems Center, San Diego, CA 92152-7383

<sup>b</sup> Segway LLC, 14 Technology Drive, Bedford, NH 03110

<sup>c</sup> Science and Technology Associates, Inc., 4100 N. Fairfax Dr., Arlington, VA 22203

<sup>d</sup> SAIC, 3990 Old Town Ave., Ste. 304C, San Diego, CA 92110

<sup>e</sup> DARPA IPTO, 3701 N. Fairfax Dr., Arlington, VA 22203-1714

## ABSTRACT

The Segway Robotic Mobility Platform<sup>TM</sup> (RMP) is a new mobile robotic platform based on the self-balancing Segway Human Transporter (HT). The Segway RMP is faster, cheaper, and more agile than existing comparable platforms. It is also rugged, has a small footprint, a zero turning radius, and yet can carry a greater payload. The new geometry of the platform presents researchers with an opportunity to examine novel topics, including people-height sensing and actuation modalities. This paper describes the history and development of the platform, its characteristics, and a summary of current research projects involving the platform at various institutions across the United States.

**Keywords:** Segway Robotic Mobility Platform, Segway RMP, dynamic self-balancing robot

## 1. INTRODUCTION

The Segway RMP is a hardware component that has been developed under a program whose objectives focus on the development of software: the Defense Advanced Research Projects Agency (DARPA) Mobile Autonomous Robot Software (MARS) program.<sup>1</sup> The reason for this is that the validation of autonomous capabilities always requires testing on physical robots in real world environments, and this requires physical hardware: robotic vehicles, sensors, and computers. Too often the cost of these components, coupled with the cost of performing experimentation and testing, diverts both financial resources and management attention from the primary program goals. “Traditional” platforms for mobile robot research (which include oversized “toy cars” such as the Pioneer and large upright “trash can” robots such as the Nomad) have been limited in terms of both payload capacity and mobility characteristics, including speed. Moreover, some commercially available research robot platforms have obliged researchers to use specific (often proprietary) computing architectures and software development environments not of their own choosing.

The Segway RMP is a platform designed to circumvent many of these limitations. It is capable of high speed (~13 km/h) indoor and outdoor operation (albeit over benign terrain), capable of turning in place, affords a human-height sensor point of view, and has a payload capacity of up to a hundred kilograms. It is easy to mount sensors and effectors on the platform, and to change the configuration with minimum effort. The Segway RMP can travel on the order of 15 km between recharges from any standard AC outlet. The hardware interface to the Segway RMP is via CAN bus (with a USB interface to be available soon); the software interface is via a simple high level API. Perhaps most importantly, the researcher doesn't have to be concerned with cross compiling code and downloading it to an embedded processor—with the Segway RMP, *you don't download the code, you simply download your laptop*. In brief, the Segway RMP is designed to let software researchers focus their efforts on the task of developing software, while affording the opportunity to exercise that software in real world environments with minimum cost in dollars, time, and effort.

The genesis of the Segway RMP was a visit by the MARS Program Manager to DEKA and Segway LLC in February 2002. A brief introduction to the Segway Human Transporter (HT) strengthened his sense that the HT could form the basis for a highly capable low-cost platform for research in mobile robotics. (Independently, NASA also envisioned the robotic use of the Segway HT, producing an artist's sketch of Robonaut mounted on the HT control shaft.) In late summer 2002, Segway LLC agreed to support the development of an RMP based on the I-series

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\*E-mail: [hoa.nguyen@navy.mil](mailto:hoa.nguyen@navy.mil)

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| 14. ABSTRACT<br><b>The Segway Robotic Mobility Platform™ (RMP) is a new mobile robotic platform based on the self-balancing Segway Human Transporter (HT). The Segway RMP is faster, cheaper, and more agile than existing comparable platforms. It is also rugged, has a small footprint, a zero turning radius, and yet can carry a greater payload. The new geometry of the platform presents researchers with an opportunity to examine novel topics, including people-height sensing and actuation modalities. This paper describes the history and development of the platform, its characteristics, and a summary of current research projects involving the platform at various institutions across the United States.</b>                                                                                                                     |                                    |                                     |                                                                  |                                                     |                                    |
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Segway HT. In late 2003 additional funding was provided to Segway LLC to produce a version of the RMP based on the (smaller) "P" version of the HT, and four of these were delivered in April 2004. Finally, in May 2004, Segway LLC offered the RMP as a commercial product (Fig. 1).<sup>2</sup>

Section 2 of this paper discusses the acquisition and distribution of the initial Segway RMPs, section 3 describes the technical characteristics of the RMP in considerable detail, section 4 summarizes its current usage among the research community, and section 5 describes the research that has been performed using the RMP by the various MARS investigators. While the RMP was developed to support the researchers of the MARS program, it is clear that a robust version of the RMP might enable robotic solutions in many real-world application domains, both military and civilian. Section 6 describes some of the initial thinking along these lines.

## 2. ACQUISITION AND DISTRIBUTION

SPAWAR Systems Center (SSC), San Diego was funded by DARPA in August 2002 to serve as the Technical Director for the acquisition and distribution of Segway RMPs, and training the users. SSC San Diego purchased Segway HTs which were then converted to Segway RMPs and distributed to DARPA MARS researchers for use in their laboratories. SSC San Diego played a key role in the development of the Segway RMP by interfacing with DARPA, Segway LLC, and researchers during the initial phase in order to ensure that the platforms were distributed efficiently and that issues and concerns encountered by researchers were quickly addressed.

### 2.1. History

In August 2002, SSC San Diego placed a purchase request with Segway LLC for 18 Segway HTs and supporting user training. The platforms were received in November 2002 and the user training was supplied on-site by Segway LLC for government personnel. Once trained, SSC San Diego personnel conducted various ad hoc terrain, stability, and mobility tests to gain a more comprehensive understanding of the platform's capabilities. A member of the SSC San Diego Segway RMP project team was certified as a Segway HT trainer in order to conduct training sessions for MARS research institutions designated to receive a Segway RMP. The idea was that researchers who would work with RMPs should be familiar with the characteristics of the platform from which they were derived.

In January 2003, Segway LLC was awarded a contract to develop hardware kits to convert the HTs into RMPs, and the associated operating software. In April 2003, Segway LLC demonstrated the RMP at the MARS Program Review Meeting in San Diego. This was the first opportunity for the researchers to experience the unique characteristics of the RMP and to begin to brainstorm about the ways that their sensors and other robotic hardware could be used with this new platform. They also received Segway HT user training at SSC San Diego (Fig. 2).



**Figure 1.** The Segway RMP (initial units had a rectangular top plate).

### 2.2. Segway RMP Conversion and Distribution

In June 2003, SSC San Diego began executing 'bailment agreements' between SSC San Diego and MARS research institutions for the use of the RMPs. Prior to shipping, Segway HTs were converted into RMPs at SSC San Diego through installation of the conversion kits and software modifications. Twelve of the RMPs were initially distributed to: Carnegie Mellon University, Georgia Institute of Technology, Massachusetts Institute of Technology, National Aeronautics and Space Administration, National Institute of Standards and Technology, Naval Research Laboratory, Stanford University, University of Massachusetts, University of Michigan, University of Pennsylvania, University of Southern California, and Vanderbilt University, with a unit later going to the Neurosciences Institute.<sup>3</sup> SSC San Diego retained the remaining RMP platforms for further research and development efforts (see Section 5). MARS researchers were responsible for providing a dual-channel CAN card along with items such as laptop computer, joystick, or other control hardware.



**Figure 2.** MARS researchers received Segway HT training at SSC San Diego.

### **2.3. Segway RMP Virtual Project Office**

The Segway RMP User Group was formed to support collaboration between the MARS research groups. One of the tools used to unite the group was an interactive website hosted by SSC San Diego. This website was a password-protected “Virtual Project Office (VPO),” based on a standard template provided by SSC San Diego and customized to meet the needs of the Segway RMP User Group.

The Segway RMP User Guide and Programming Interface documents were posted to a document library inside the website. Images and videos of the various RMP prototypes and training sessions were also included in the library. Additionally, each Segway RMP User Group member was listed in a directory, and a message board was provided where questions could be posted for discussion among the members.

The website was heavily used during the initial training and distribution period, and proved extremely valuable for identifying several problems that surfaced almost immediately. The Segway RMP User Group community debated possible solutions, along with engineers from Segway LLC, and fixes were posted on the website, making it easily accessible for immediate download. It was also a great resource for subsequent Segway RMP Users. Relevant material was readily available that facilitated quick integration of the RMP into their development efforts. This website was an example of how quickly engaging a diverse research community, and clearly communicating potential problems and fixes, can enhance and accelerate the adoption of new technology.

Over the course of the year, SSC San Diego imposed stricter security regulations on VPO use, making access less user friendly. At the same time, as the Segway RMP became commercially available, more resources were provided by Segway LLC to support RMP users. As a result, the VPO web site was ramped down in the last quarter of 2004, and a Segway RMP User Group discussion website is now supported by Segway LLC.<sup>4</sup>

## **3. CHARACTERISTICS**

The overall objective of the Segway RMP development project was to quickly create a minimally modified machine. Segway LLC leveraged the design of the Segway HT to the highest possible degree, which created a robust design in a three-month period. The primary modifications involved changes to firmware and creation of an electrical interface to the RMP. The existing HT design offered the possibility of creating a reliable and robust system quickly, but it also constrained the product performance in several respects.

### **3.1 Performance Objectives for the Segway RMP**

Balancing machines present unique benefits and challenges when compared to statically stable machines. For example, a balancing machine can turn with zero radius and can carry a large payload much higher than a comparable weight statically stable base. But dynamically stabilized machines can fall over and “the taller they are, the harder they fall.”

These differences present both challenges and opportunities in mobile robot research. The RMP is not the right robot for every task, but it does offer new capabilities that solve certain problems.

Part of the Segway RMP development program involved assessing the likely applications and choosing RMP characteristics that supported the DARPA MARS program. Fig. 3 visually depicts trade-offs along two key design parameters: payload and platform height.

### 3.2 Interface

Rapid creation of a simple interface for the RMP was a primary objective of the project. Since the Segway HT utilizes CANbus to communicate with the handlebar module, the internal product development organization at Segway had been using CANbus communications throughout the development of the HT and had an existing protocol and toolset for internal use. The firmware in the HT processors was modified to receive control commands and to broadcast useful data via CANbus. PCMCIA cards are commercially available to connect a laptop to the CANbus. Additionally, several small micro controllers have been built in hardware to allow high speed CANbus communications. The command set is deliberately small—programmers may send speed and turn commands, mode change commands and counter resets to the RMP. This simple interface allows autonomy researchers to focus on the algorithms and data to produce the speed and turning commands rather than on the transportation dynamics.

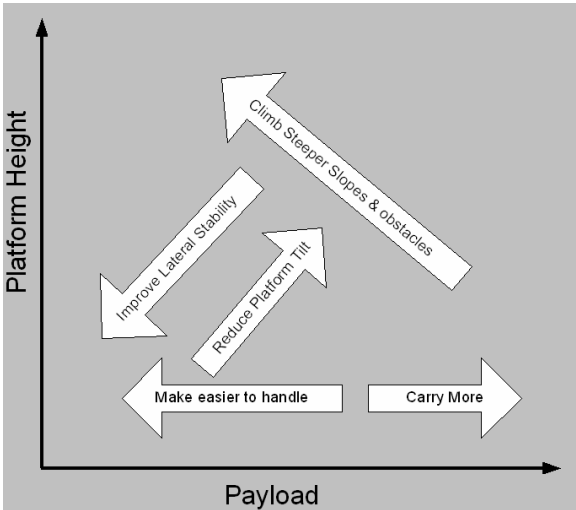


Figure 3. Segway RMP design tradeoffs.

### 3.3 Controller

Another aspect of dynamic stabilization is selection of a controller. While any feedback controller can tolerate plant variation (that is the point of feedback after all), a basic LQR controller for a balancing machine does not produce the same balancing dynamics regardless of payload. Thus the controller must be matched to the mass properties of the RMP (inertia, mass, center of gravity). Because of system loading, there was really only 1-2 KB of program memory available for the balancing controller. As a result, more elaborate adaptive schemes were not tried.

### 3.4 Performance Specifications of the RMP

The resulting dimensions and performance specifications are shown in Table 1 (although these specifications were often exceeded in actual use).

Table 1. I-series Segway RMP performance specifications.

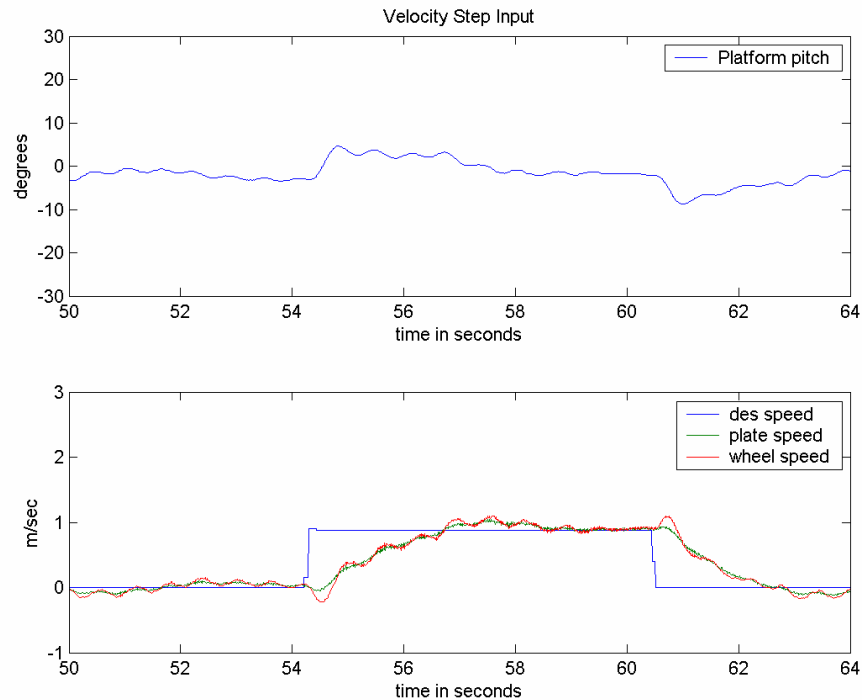
|           | Balancing | Non-balancing |
|-----------|-----------|---------------|
| Weight    | 64 kg     | 64 kg         |
| Height    | 76 cm     | 76 cm         |
| Range     | 16 km     | 16 km         |
| Payload   | 45 kg     | 90 kg         |
| Top Speed | 13 km/hr  | 13 km/hr      |

### 3.5 General Characteristics of Inverted Pendulum, Balancing Machines

The dynamics of the Segway RMP are non-minimum phase in position and velocity. That is, the wheels must first move backward before the RMP can accelerate forward. This is dictated by the dynamics of the inverted pendulum. An example of this behavior is shown in Fig. 4.

As the figure shows, there is a time lag between the time the step command occurs and the RMP reaches the commanded velocity. It is also worth noting the pitch angle of the platform during the acceleration phase. Just like

sprinters in a 100 yard dash, the machine leans forward initially and then straightens up when it reaches constant velocity. In the example, a pitch of 5 degrees is observed during the initial portion of the acceleration. Greater accelerations require more pitch. Rapid acceleration and deceleration can lead to platform pitches as great as 40-50 degrees (along with a commensurate reduction in normal force!). In some applications, the tilting of the platform may be useful for increasing the effective range of a sensor. In other cases, it may introduce additional processing and sensing requirements to orient the sensor data properly.



**Figure 4.** Dynamics of the Segway RMP during acceleration and deceleration.

## 4. USAGE

Initial usage of the Segway RMP can generally be divided into three application areas: (1) as a base for a humanoid robot, (2) in human-robot teaming applications, and (3) as a general-purpose, high-mobility, rugged mobile robotic platform.

### 4.1 Humanoid Robot Applications

A humanoid robot capable of operating in an environment built for humans must possess several physical characteristics similar to humans:<sup>5</sup>

- *A small footprint:* to traverse hallways, aisles, wheelchair-accessible ramps and lifts, and turn around in close quarters,
- *Ability to place the center of mass high above the ground:* to allow the torso, head, and arms to be properly positioned to provide the visual sensing and manipulation capabilities appropriate for built-for-human environments (e.g., ability to look over and manipulate objects on a work surface, operate door knobs, open cabinets, etc.),
- *A tilt axis close to the floor:* to allow the robot to balance by redistributing its weight while reaching out with its arm (similar to the tilting action provided by the ankles in humans), and
- *A resistance to unexpected lateral forces:* to remain balanced while encountering unexpected perturbations.

A statically stable platform (i.e., with three or more wheels) cannot satisfy all of these seemingly contradictory requirements. To allow a high center of mass and provide resistance to unexpected lateral forces, the footprint would have to be large to remain stable. Redistribution of weight would require an additional axis of mobility above the



platform. These capabilities can only be provided by either a bipedal lower body or a dynamically balancing wheeled platform such as the Segway RMP. While a bipedal lower body provides more capabilities (e.g., stepping over obstacles and stair climbing), providing mobility for a bipedal humanoid robot is a difficult problem. Humanoid robotic researchers concentrating on intelligence, human-interaction, and manipulation have been able to sidestep or postpone tackling this problem by using the Segway RMP.

The Segway RMP has a small footprint (especially the newer P-series), *prefers* a high center of mass (which makes balancing easier), has a natural tilt axis close the floor (the wheel axis), and its self-balancing ability provides natural resistance to lateral forces (it would move in response to lateral forces, and lean *into* the direction of the force, to remain upright).<sup>6</sup>

Among the organizations with Segway RMPs from the SSC San Diego-managed pool, NASA Johnson Space Center and the Massachusetts Institute of Technology are using them as platforms for humanoid robots.

## 4.2 Human-Robot Teaming Applications

There are several ways humans and robots work as a team, depending on the desired leader/follower roles. However, to team as equal peers, the robot and humans should have similar physical and mobility characteristics. The availability of the Segway platforms in both robotic and non-robotic forms (i.e., Segway RMPs and HTs) makes them ideal for studies of the teaming of humans and robots as peers.

Carnegie Mellon University and the Neurosciences Institute are studying human-robot interactions using mixed teams of autonomous RMPs and humans riding Segway HTs in soccer games. This is probably the first ever experiments involving both humans and robots, with similar capabilities, interacting in both cooperative and adversarial roles.

## 4.3 General-Purpose High-Mobility Platform

Besides its ability to act as a platform for robotic research in built-for-human domains, the Segway RMP is also an exceptional general-purpose robotic platform. Some of its selling points include:

- *Ruggedness*: Built from a commercial platform produced for the mass consumer market, the Segway RMP is much more rugged than other robotic platform comparable in size and weight. It has demonstrated ability to survive repeated falls, including an unintentional fall off a high cliff.
- *Payload capacity*: The RMP can carry a heavy payload for a platform with its size and weight: over 45 kg in balancing mode, and over 100 kg in non-balancing (tractor) mode.
- *High mobility*: The RMP can travel at significant speed (up to 13 km/h) over varied terrain, and has a zero turning radius.
- *Economy*: Built from a mass-produced commercial platform, the RMP can be acquired for less than half the price of other platforms with comparable payload capacity.
- *Stability*: Some researchers have reported that the RMP's dynamic stabilization has actually resulted in video streams from on-board cameras that are more stable over rough terrain than those captured from four-wheeled robotic platforms.

There are also some obvious weaknesses associated with this new platform. These include the loss of balance due to wheel slippage on loose sand and shrubs, as well as the inability to remain upright in case of power, hardware, or software failure. To address these problems, some researchers have installed static outriggers or automatically-deployed kickstands that triggers on fault conditions.

# 5. RESEARCH APPLICATIONS

Below are summaries of applications of the Segway RMPs at some of the research institutions that received the platforms from SSC San Diego.

## 5.1 National Aeronautics and Space Administration (NASA)

NASA Johnson Space Center has integrated a Segway RMP base with the highly dexterous humanoid robot, Robonaut, designed to work side-by-side with astronauts on extravehicular activities (EVAs)—see Fig. 5. The combined robotic system demonstrates the mobility and manipulation skills that are required for advanced EVA missions. While realizing

that the Segway RMP is not suitable for space, NASA is using it as an inexpensive, mobile lower body for earth-based testing of the Robonaut, and for studying coordinated control of dexterous limbs on a mobile robot. The self-contained system also allows easier transportation to various offsite facilities for demonstration and teaching purposes.

Robonaut Unit B is mounted on the Segway RMP after its single seven-DOF stabilizing leg was removed (except for the single joint at the waist, which helps increase the arms' effectiveness). Telepresence control is provided through virtual reality helmet, gloves, and body tracking sensors. A pair of foot pedals was added for control of the mobility base,<sup>7,8</sup> as well as a set of outriggers with roller bars for safety.

One of the problems initially encountered when Robonaut and the RMP were first integrated was an incorrect balance gain schedule. The Robonaut is much heavier than normal sensor and effector payloads intended for the RMP. This caused excessive motion of the RMP until a customized balance gain schedule was created for the system by Segway LLC.

With the RMP providing mobility, Robonaut has demonstrated the ability to open doors, use tools from various fixtures, and cut single wires from wire bundles. Additional autonomous capabilities for navigation, human following, and taking objects (such as a wrench) from a human were demonstrated at the DARPA Tech conference in March 2004 in Anaheim, CA.

## 5.2 Massachusetts Institute of Technology (MIT)

MIT's Humanoid Robotics group has been working on a number of robotic humanoid heads and torsos. Until the Segway RMP became available, none of them had been able to move about. Mobility is complicated in humanoids, and the group's emphasis has been on humanoid intelligence and human interaction. Using the Segway RMP, MIT created Cardea (Fig. 6).

MIT's goal is to create robots that can function in human-centric environments. The Segway RMP allows Cardea to stand as tall as a human without the need for an awkwardly wide base for stability. The first task chosen for demonstration is for the robot to navigate through corridors and rooms of an office environment, to find and open (slightly ajar) doors, and to go through them.<sup>5</sup>

Currently, Cardea's manipulator is a single 5-DOF arm built with Series Elastic Actuators that deliver human-like compliancy. The arm ends in a stump, although there are plans to add a hand in the future. Cardea is equipped with ten sonar sensors, two touch whiskers, and two cameras (a fixed camera for navigation, and an actively panning camera for detecting doors). A set of spring-loaded kickstands deploy whenever a fault condition develops. There are plans to add a stereo vision system, two more arms, and an expressive face. Eventually, MIT researchers hope Cardea will be able to recognize and develop relationships with people around it, and learn about its environment by handling objects in it.



Figure 5. The NASA Robonaut RMP.



Figure 6. MIT's Cardea with kickstand extended.

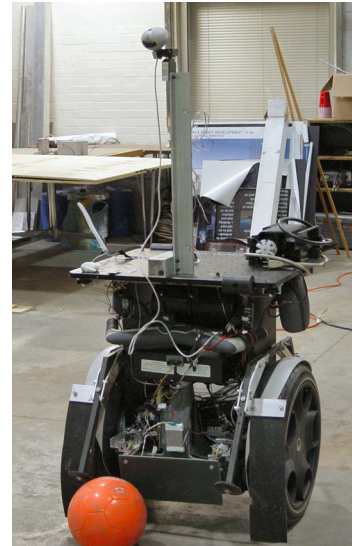


### 5.3 Carnegie Mellon University (CMU)

Capitalizing on the RMP's human-like size, weight, and balancing ability, CMU is using Segway RMPs and HTs to create a new domain for studying human-robot interaction in peer-based teams, namely Segway Soccer.<sup>9</sup> Each team would probably include two units of each type. The RMP is ideally suited to this domain since its dynamic balancing gives the robot a measure of active compliance very useful when collisions occur.<sup>10</sup>

CMU's research effort with the RMP over the last year has focused on building the individual capabilities a robot needs to operate autonomously within a soccer-playing team, including:

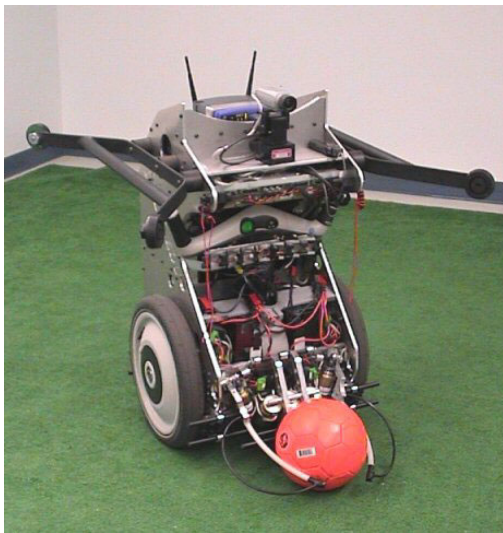
- *Developing real-time, robust, and adaptable vision algorithms:* the only additional sensor added to the RMP for soccer playing was a color Web camera; the color blob extracting CMVision library was extended to detect contrasting objects under variable illumination conditions;
- *Developing ball manipulation hardware:* a pneumatic kicking mechanism was designed to impart maximum energy to the ball;
- *Developing robust multi-object tracking techniques with real-time implementations:* including efficient recognition of the multiple objects relevant to the human-robot game, namely the ball, the goals, the field markers, and the other robot and human teammates and opponents;
- *Developing skill-learning algorithms:* to eliminate the time-consuming and error-prone process of tuning individual skills, a skill recording system was developed, whereby a human operator guides the robot via tele-operation through a complex motion, with the robot commands recorded to a file that can be later played back as an acquired skill.<sup>11</sup>



**Figure 7.** CMU's soccer-playing RMP.

Besides pioneering the development of this domain within the RoboCup competition framework, CMU is also trying to attract other groups to participate in this effort, with the Neurosciences Institute being one of the early participants.

### 5.4 Neurosciences Institute (NSI)



**Figure 8.** NSI's soccer-playing RMP.

The Neurosciences Institute's research focuses on the development of Brain-Based Devices—physical devices with simulated nervous systems—as a means to understand brain functions. By having their designs based on neurobiological principles, Brain-Based Devices (BBD) have demonstrated behaviors similar to biological organisms that would have been difficult to achieve with a conventional system.<sup>12</sup>

Institute researchers recently created a BBD using the Segway RMP specifically designed to play soccer (Fig. 8). The Segway RMP, with its high mobility, ruggedness, and payload capacity, allowed the institute's researchers to take a BBD outdoors for the first time. Additional sensors and effectors added to the RMP include: a CCD camera to recognize objects on the field (e.g. balls, teammates, goals, etc), infrared (IR) sensors to detect the ball and obstacles, and solenoids to capture and kick the ball. The device's behavior is guided by a neural simulation that receives input from the camera and IR sensors, and generates motor signals to the wheels. The neural simulation models the visual cortex for color and shape processing, the motor cortex for behavioral responses, and a value system that responds to salient objects and modulates learning.<sup>13</sup>

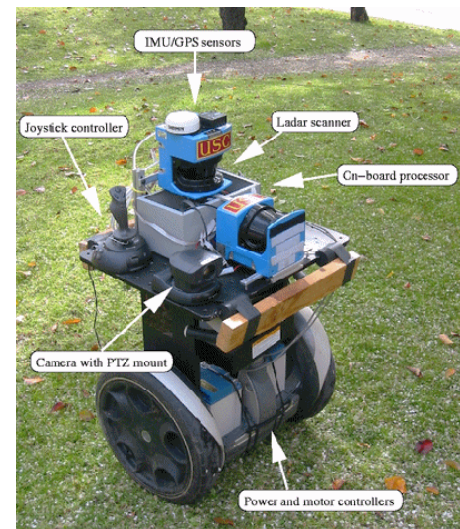
To date, the physical designs and control methodology of the soccer playing RMPs from the Neurosciences Institute and Carnegie Mellon University have been very different. It will be interesting to compare and contrast these approaches when they play together in the first Segway RoboCup competition.

## 5.5 University of Southern California (USC)

The University of Southern California's Robotics Research Lab has used the Segway RMP as a platform for research in mapping, localization, stealthy navigation, and path planning. For experiments in 3D navigation and mapping of outdoor urban environments, the RMP was equipped with one SICK laser in the horizontal plane and one or more ladars in the vertical plane (Fig. 9). The horizontal ladar was used for fine-scale localization, while the vertical ladars were used to generate dense 3D maps. The RMP was selected for this task because of its speed, endurance, large payload capacity, and high vantage point for sensors, which helped eliminate ground clutter.<sup>14</sup>

USC researchers have also developed algorithms for the robot to detect independent motion from a moving platform, to track and follow people in the environment,<sup>15,16</sup> to navigate stealthily using opportunistic and dynamic cover,<sup>17</sup> and to plan optimal paths on uneven outdoor terrain under dynamic constraints.<sup>18</sup> For some of these experiments, USC employed the Segway RMP in conjunction with other robots with vastly different motion characteristics, such as a Pioneer 2-AT and a robotic helicopter, to show the generality of the solutions.

One other significant contribution USC has made to the Segway RMP research community is the provision of the Segway model and drivers for their Gazebo 3-D simulator and Player/Stage multi-robot device server and simulator<sup>19</sup> (with initial Player driver contributed by University of Massachusetts).<sup>20</sup> A number of other research groups are using these open-source tools for simulation and control of their RMPs.



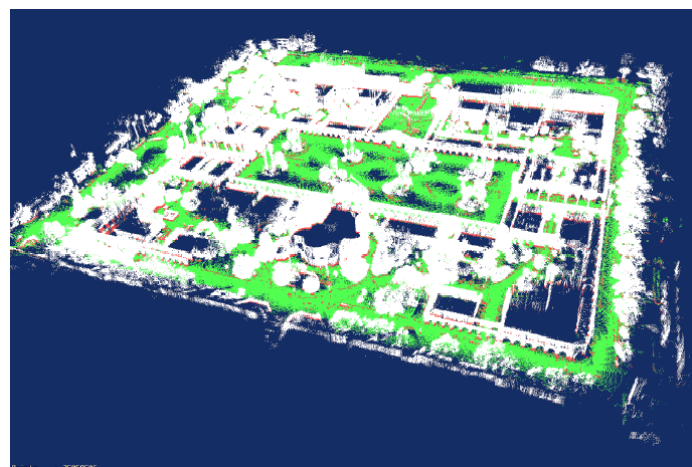
**Figure 9.** USC's RMP.

## 5.6 Stanford University

The Stanford Artificial Intelligence (AI) Lab is using a Segway RMP as the main component of a mobile robot system (named the Segbot—see Fig. 10) for 3-D mapping and navigation in outdoor environments. The navigation algorithm finds a path through the map that maximizes progress to a target while minimizing the probabilities of encountering non-traversable space. The RMP is equipped with a SICK ladar mounted on its side and swept back and forth by an Amtec pan-and-tilt unit to acquire 3-D scans of the environment. The RMP also carries an Inertial Measurement Unit and GPS for localization. By integrating data from the IMU, GPS, and laser scans, globally consistent 3-D maps of urban environments are constructed (Fig. 11).<sup>21</sup>



**Figure 10.** The Stanford Segbot with side-sweeping ladar.



**Figure 11.** A 3-D map of the central area of the Stanford campus generated by the Segbot.

## 5.7 University of Michigan (UMich)

Mobile robots generally use a combination of gyroscopes and odometry for dead-reckoning. However, if the terrain is not level, the slope contributes significant errors in the position estimation. The Mobile Robotics Lab at the University of Michigan has developed a Fuzzy Logic Expert rule-based navigation (FLEXnav) method for fusing data from multiple gyroscope and accelerometers to estimate the heading and tilt of a mobile robot. The outputs of the fuzzy fusion system are weighting factors that emphasize the gyroscope readings, the accelerometer readings, or weight one relative to the other. This information is further integrated with wheel encoder data to more accurately determine the position of the robot.

The Segway RMP, however, introduces a significant problem to this solution. The RMP changes pitch as a function of its dynamic stabilization method. The pitch as measured by platform-mounted sensors does not represent the pitch of the terrain, as is for statically stable four-wheeled platforms. To solve this problem, UMich researchers installed two downward-looking IR range sensors underneath the bumpers of their Segway RMP. These sensors measure the pitch of the platform relative to the terrain, which, in combination with the measured pitch from the platform-mounted sensors, determines the true pitch of the terrain. With this setup, experiments showed that the RMP can traverse a 3-D environment with errors of only approximately 0.15% after 75 meters of travel.<sup>22</sup>

With FLEXnav providing accurate positioning, UMich researchers are using the Segway RMP for studies of terrain mapping, traversability analysis, and path planning. It was found that the natural pitching motion of the RMP as it travels even on flat terrain has a unique advantage: It provides the rigidly mounted ladar a wider vertical field of view.<sup>23</sup>

## 5.8 University of Pennsylvania (UPenn)

The University of Pennsylvania's General Robotics, Automation, Sensing, Perception (GRASP) Laboratory is a member of a joint DARPA MARS 2020 research group that also includes USC, the Georgia Institute of Technology, and BBN Technologies. The goal of this joint project is the development of critical technologies for network-centric control of a team of heterogeneous robotic platforms for reconnaissance, surveillance, or search and rescue missions. UPenn's focus is on software architecture, communication-sensitive behaviors, terrain adaptation, and computationally distributed situation awareness.<sup>24</sup> As part of this effort, the Segway RMP is being evaluated for use as an all-terrain ground robotic platform that will be able to carry a significant weight without sacrificing maneuverability. Extensive tests were conducted to characterize the RMP's capabilities and limitations. Demonstrations of color blob tracking and people following were also conducted.<sup>25</sup>

## 5.9 Georgia Institute of Technology (Georgia Tech)

The Mobile Robot Laboratory at the Georgia Tech has developed the MissionLab multi-agent robotics mission specification and control software (currently at version 6.0). MissionLab takes high-level military-style plans and executes them with teams of real or simulated robotic vehicles. Device drivers have been written for controlling iRobot's ATRV-Jr and Urban Robot, ActivMedia's AmigoBot and Pioneer AT, and Nomadics Technologies' Nomad 150 and 200. Each vehicle executes its portion of the mission using reactive control. Georgia Tech ported MissionLab to the RMP and used it as a member of the family of platforms supported by the software. The RMP was equipped with a ladar and camera to support operation under MissionLab. The system was demonstrated in convoying mode together with Segway RMPs from USC and UPenn at the McKenna Military Operations on Urban Terrain (MOUT) site at Ft. Benning, Georgia, as part of the joint MARS 2020 project.<sup>26</sup>

Currently, Georgia Tech is working on using a ladar to generate real-time information about terrain surface roughness as input to a reactive speed control system for the RMP.

## 5.10 University of Massachusetts, Amherst

University of Massachusetts researchers are developing a new approach for multi-objective control using a cascade of filters that progressively removes candidate commands that do not satisfy task constraints. The application chosen for demonstration is a leader/follower task in which a Segway RMP must address the potentially conflicting objectives of moving to a goal location (following a leader) while avoiding obstacles and keeping the goal region within the field of view of a fixed camera. Motion primitives were demonstrated for reactive navigation and global navigation at high velocities in an outdoor setting on the RMP.<sup>27</sup> A simple but effective safety system made of PVC pipes was also developed to protect the on-board equipment in case of a system failure (see Fig. 12). The system includes kill switches



in the legs that will shut down the RMP if any foot touches the ground (a condition that would lead to a runaway state due to the RMP's desire for and inability to achieve a certain attitude).<sup>28</sup> The design was later copied by a number of other research groups.

### 5.11 Vanderbilt University

Vanderbilt University developed and has been performing research on a humanoid robot called ISAC (Intelligent Soft Arm Control). ISAC has an upper torso, head, and two arms, but is otherwise non-mobile. Unlike MIT and NASA, who installed their humanoid torsos on the Segway RMP mobile platform, Vanderbilt took a different approach. The Segway RMP is used as the base for a helper robot that brings objects and tools into the workspace of the stationary ISAC (Fig. 13). Work is progressing on the merging of the two robots so that they become in principle a single "distributed robot." This is accomplished by the sharing of a memory structure known as the Sensory Ego Sphere (SES). ISAC would use the SES information from the Segway RMP to control the position and orientation of the Segway in order to gain access to a specific tool.<sup>29</sup>



Figure 12. UMass RMP with safety system.

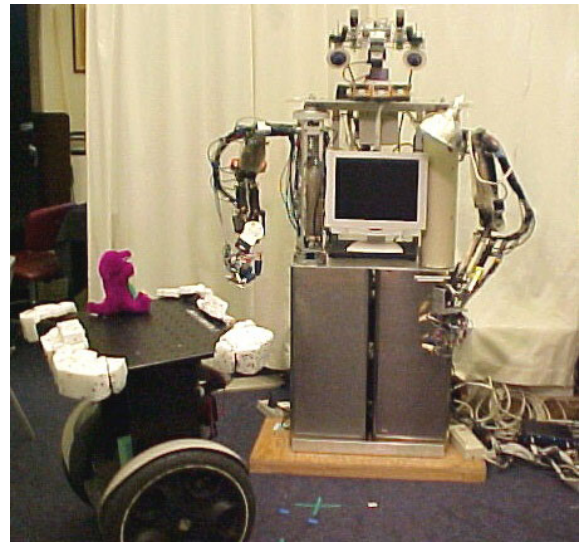


Figure 13. Vanderbilt's ISAC and RMP.

## 6. MILITARY APPLICATIONS

SSC San Diego has been exploring military applications for the Segway platforms, including: (1) performing extensive testing of the HT on various terrain, (2) providing mobility to the Life Support for Trauma and Transport (LSTAT) system, (3) demonstrating technologies for a small logistics transportation system, and (4) acting as a lead robot for underground bunker explorations, demonstrating the utility of autonomous mobile communication relay robots. We will briefly summarize (1), (2), and (3) here. Tasks (2) and (3) are described in detail in another paper at this same conference.<sup>30</sup> Task (4) has been described elsewhere.<sup>31</sup>

### 6.1 Terrain Testing

SSC San Diego performed extensive testing of the Segway Human Transporter (HT) to evaluate the usefulness of the system in military environments. Many environments present situations in which a full size military vehicle is not a viable means of transport. The HT's ability to transport a person up to four times walking speed while taking up very little space provides a capability not currently available.

The testing clearly showed that for many types of terrain the Segway significantly increased average speed of the operator over the speed of a walking person. However, as terrain roughness and the size of obstacles in the path increased, the utility of the HT decreased, and eventually yielded worse performance than walking. Terrain types which yielded poor traction, such as thick sand and wet or slippery vegetation, also decreased the HT's performance. In

addition, testing showed that by replacing the standard HT tires with high traction tires (Fig. 14) the HT's performance was maintained through a higher grade of terrain roughness and larger obstacles. Conversely, the high traction tires also significantly reduce battery life. Similar traction/battery life results occurred to a lesser degree when traction was increased by decreasing air pressure in the standard tires. Overall, when used with good judgment and in the proper applications, the Segway HT can significantly reduce transportation time for the operator in many terrain types.<sup>32</sup>

## 6.2 Roboticized LSTAT

The Life Support for Trauma and Transport (LSTAT) is a portable intensive care system developed by Integrated Medical Systems (IMS). The system allows for an injured person to be treated in situations and/or at locations where advanced medical equipment would not otherwise be available. The system includes a ventilator, a suction system, an oxygen system, an infusion pump, a clinical blood analyzer, a defibrillator, and a physiological monitor.

With a total weight, including patient, of approximately 160kg, currently two to four persons are required to transport an LSTAT. To facilitate the transport and care of large numbers of injured persons, SSC San Diego explored the feasibility of a roboticized LSTAT. The prototype (Fig. 15) was constructed from an RMP operating in non-balancing mode, a hitch, a standard NATO litter carrier, and a fully weighed LSTAT shell (using sand bags—an actual LSTAT was not used due to the cost involved). The system successfully demonstrated litter and patient transport through interior corridors, on sidewalks, and over paved streets. The system also performed surprisingly well in an all-terrain environment. However, the high center of gravity created a stability problem over extremely rough terrain with loose soil and dried scrub brush.<sup>30</sup>



Figure 14. Terrain testing of the Segway HT.



Figure 15. Segway RMP transporting an LSTAT mock-up.

## 6.3 A Logistics Transporter

In the area of logistics transport, there currently is a gap between the one-ton Army robotic MULE and the soldier's backpack. SSC San Diego, with the assistance of a group of interns from nearby High Tech High School, has demonstrated enabling technologies for a solution that fills this gap. A small robotic transport system was developed using the Segway RMP in tractor mode, capitalizing on the power, ruggedness, size, and economy of the platform. Two demonstrations of autonomous behaviors were conducted. Both demonstrations involved a human leading the robotic transporter. In one, the transporter used a vision system running a *continuously adaptive mean-shift filter* to track and follow a human. In the second demonstration, the separation between leader and follower was significantly increased to several hundred meters (limited by the range of the 802.11b communication link) using GPS information. The track of the human leader, with a GPS unit and laptop computer in his backpack, was sent wirelessly to the robotic transporter, which was also equipped with a GPS unit. The robotic transporter traced the path of the human leader by following these GPS breadcrumbs (see Fig. 16).<sup>30</sup>



**Figure 16.** The Segway RMP-based logistics transporter.

## 7. CONCLUSION

We are witnessing the dawn of a new robotic mobility platform. Based on the commercially available Segway Human Transporter, the Segway RMP has introduced new perspectives in robotic sensing, manipulation, and mobility. Its human height, size, agility, and ability to host people-height payloads make it ideal for humanoid and robot-human interaction research, while its ruggedness, speed, weight-carrying capacity, and price make it attractive as a general-purpose outdoor robotic platform. We have summarized here the work at twelve research institutions using the platform. They range from use as simpler alternatives to humanoid legs, and autonomous robot soccer players, to general mobility power plant for pulling logistics carts. With time, we are certain that more novel uses of the Segway RMP will continue to be discovered.

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