Recent Developments of the HLPR Chair

(Home Lift, Position and Rehabilitation Chair)

Roger Bostelman, James Albus, Tommy Chang

Abstract—**The Home Lift, Position and Rehabilitation (HLPR) Chair, developed at the National Institute of Standards and Technology (NIST) within the Intelligent Systems Division (ISD) from 2005 to 2006, is currently being evaluated for static stability using computer aided design. The HLPR Chair has a unique shape as compared to conventional wheelchairs and powered chairs. Therefore, evaluation of its stability is necessary to ensure rider safety. Also, the HLPR Chair was originally designed and built with only manual controls. Recently, the HLPR Chair has been transitioned towards an autonomous patient mobility device to evaluate its performance for navigation by less cognizant drivers, such as patients with early signs of dementia. Preliminary electronics, software drivers and calibrations have been completed. Also, a plan has been developed for providing fully autonomous HLPR Chair capability based on previous defense project developments at NIST using a standard control architecture called 4 Dimensional/Real-time Control System (4D/RCS). Approximated stability evaluation, control developments and autonomous control plans are described in this paper.**

I. Introduction

IN the United States, over two million individuals cannot functionally ambulate [1]. Two categories of technology are pivotal to the daily living of individuals who are non-ambulatory – mobility aids and transfer aids. A review of the current durable medical equipment offerings indicates a substantial disparity exists between wheeled mobility and transfer technology. Modern wheelchair technology has evolved into a highly sophisticated, consumer-centered product line. Wheelchairs can be personalized with seating, custom controls and special features such as powered postural supports, seat elevators, manual and power standing wheelchairs are available. In contrast, methods and technology to assist consumers in transferring between wheelchairs and other locations are arguably primitive. The majority of transfers are still accomplished as they were a century ago; manual lifting by caregivers, use of a lacquered sliding board, or sling lifts with most of the power provided by the caregivers.

Pollak [2] states that "today, approximately 10 percent of the world's population is over 60; by 2050 this proportion will have more than doubled" and "the greatest rate of increase is amongst the oldest old, people aged 85 and older." Pollak follows by adding that this group is subject to both physical and cognitive impairments more than younger people. These facts have a profound impact on how the world will maintain the elderly independent from caregivers as long as possible. Diminishing physical and cognitive abilities address both the body and the mental process of knowing, including aspects such as awareness, perception, reasoning, intuition and judgment. With fewer caregivers and more elderly, there is a need for improving assistive devices to provide them independent assistance.

There are many more references that reiterate the need for patient lift and mobility devices relieving the need for caregivers [3, 4, 5, 6, 7, 8, 9]. These state that mobility is fundamental to health, social integration and individual well-being and that relieving the dependence on the wheelchair is ideal for this type of patient to live a longer, healthier life.

In 2005, the National Institute of Standards and Technology (NIST) Intelligent Systems Division (ISD) began the Healthcare Mobility Project to target this staggering healthcare issue of patient lift and mobility. ISD researchers looked at currently available technology through a survey of patient lift and mobility devices [10]. That project showed that there is need for technology that includes mobility devices that can lift and maneuver patients to other seats and technology that can provide for rehabilitation to help the patient become independent of the wheelchair.

NIST has also been studying intelligent mobility for the military, transportation, and the manufacturing industry for nearly 30 years through the Intelligent Control of Mobility Systems (ICMS) Program [11]. NIST has begun outfitting the HLPR Chair with computer controls based on a NIST-developed control system architecture and advanced 3D imaging technologies currently being researched within the ICMS Program. Although throughout the world there are, or have been, many research efforts in intelligent wheelchairs, including [12, 13, 14, 15] and many others, the authors could find no sources applying standard control methods nor application of the most advanced 3D imagers prototyped today to intelligent wheelchairs. Therefore, NIST began developing the HLPR Chair to investigate these specific areas of mobility, lift and rehabilitation, as well as advanced autonomous control.

This paper includes discussion of recent developments on the HLPR Chair, first briefing the reader on its design and then a section covering recent stability testing. Following are sections on the recent HLPR Chair modifications towards integrating intelligent control and a plan for a near-term demonstration. Conclusions and future work, acknowledgments and references close the paper.

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II. HLPR CHAIR STRUCTURE AND MOBILITY DESIGN

The HLPR Chair [16] prototype, shown in Figure 1, is based on a manual, steel, inexpensive, off-the-shelf, and sturdy forklift. The forklift includes a U-frame base with casters in the front and rear and a rectangular vertical frame. The lift and chair frame measure 58 cm (23 in) wide by 109 cm (43 in) long by 193 cm (76 in) high (when not in the lift position) making it small enough to pass through even the smallest, typically 61 cm (24 in) wide x 203 cm (80 in) high, residential doors. The HLPR Chair frame could be made lighter with aluminum instead of steel.

The patient seat structure is a double, nested and inverted L-shaped frame where the outer L is a seat base frame that provides a lift and rotation point for the inner L seat frame. The L frames are made of square aluminum tubing welded as shown in the figure. The outer L is bolted to the lift device while the inner L rotates with respect to the seat base frame at the end of the L as shown in the photograph. The frame's rotation point is above the casters at the very front of the HLPR Chair frame to allow for outside wheelbase access when the seat is rotated 180º and is the main mechanism through which access to other seats is possible. Drive and steering motors, batteries and control electronics along with their aluminum support frame provide counterweight for the patient to rotate beyond the wheelbase. When not rotated, the center of gravity remains near the middle of the HLPR Chair. When rotated to 180º with a 136 kg (300 lbs) patient on board, the center of gravity remains within the wheelbase for safe seat access. Heavier patients would require additional counterweight.

The HLPR Chair is powered similarly to typical powered chairs. Powered chairs include battery powered, drive and steer motors. However, the HLPR Chair has a tricycle design to simplify the need to provide steering and drive linkages and provides for a more vertical and compact drive system design. The drive motor is mounted perpendicular to the floor and above the drive wheel with a chain drive to it. The steering motor is coupled to an end cap on the drive motor and provides approximately 180º rotation of the drive wheel to steer the HLPR Chair. The front of the robot has two casters mounted to a U-shaped frame. The HLPR Chair has a turning radius of approximately 76 cm (30 in) which is approximately 13 % to 40 % larger than typical off-the-shelf powered chairs depending on their size. Section IV, Placement on Other Seats shows why this added length does not hinder access for a typical home activity.

The drive motor is geared such that its high speed drives a chain-driven wheel providing further speed reduction. The HLPR Chair speed is 0.7 m/s (27 in/s). While this is sufficient speed for typical eldercare needs, a more powerful motor can replace the drive motor for additional speed.

Steering is achieved through a novel single wheel design hard stopping the wheel at just beyond 180º for safety of the steering system. Steering is reverse Ackerman controlled as joystick left rotates the drive wheel counterclockwise and joystick right rotates the drive wheel clockwise. The navigation and control of the vehicle under this novel rear wheel steer and drive is currently under study and will be described in later publications.

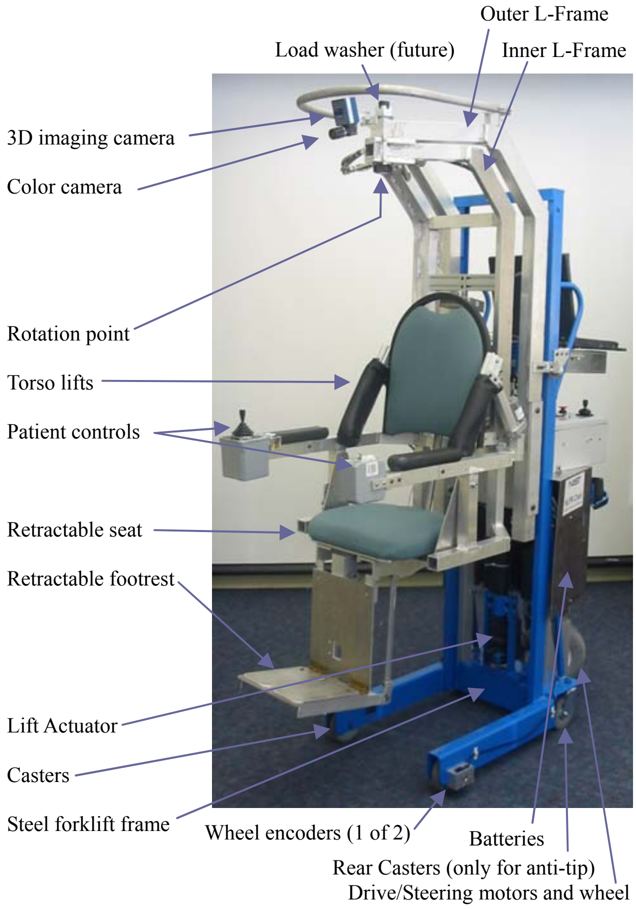


Figure 1 – HLPR Chair prototype

For access to the HLPR Chair and for mobility, the HLPR Chair is lowered as shown in Figure 2 (a and b). A seat belt or harness will be required for eldercare occupant safety. For access/exit to/from the HLPR Chair, the footrest can be retracted beneath the seat. For mobility, the footrest is deployed to carry the feet.

III. STATIC STABILITY

Manual and powered wheelchairs are assumed safe so long as they are within their designed stability limits. Maximum stability is when the rider is in the neutral or design intended position. However, leaning away from the neutral position can cause injury or even death.

The international standard for determination of static stability of wheelchairs [17] discusses these tests with wheelchairs in the forward, sideways and other directions. Initial investigations indicate that the HLPR Chair can meet the static stability requirements specified in section 9.2.1 of the standard. Forward Stability is most stable when the rear-wheel is facing back (not sideways) and the seat is in the forward, low vertical (mobility) configuration. Similarly, the HLPR Chair meets the Standard in section 12.1.1. Sideways Stability is most stable when in these same configurations.

(a) (b) (c)

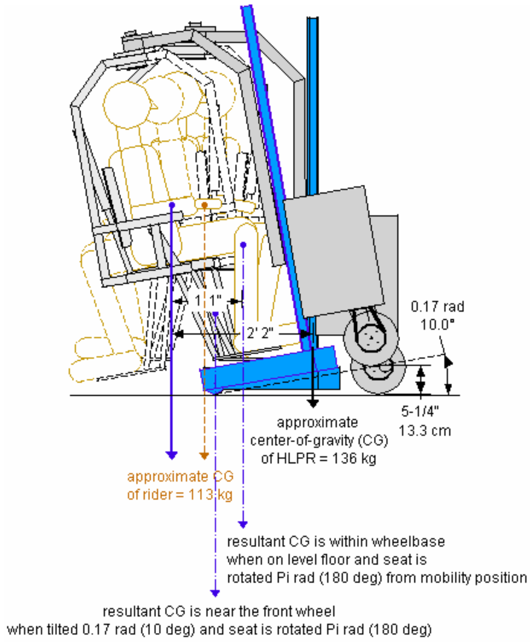
Figure 2 –HLPR Chair in the mobility configuration, showing the (a) side view and (b) front view relative to a typical doorway, and (c) the lift configuration. The maximum patient lift height is 0.9 m (36 in) above the mobility height configuration.

Figure 3 shows Computer Aided Design (CAD) models of the HLPR Chair in two directions showing static stability testing from the (a) forward and (b) sideways directions. In both configurations, the HLPR Chair is designed to withstand a 0.17 rad (10º) slope with respect to the ground without tipping even when in the least stable rotated seat configuration. Therefore, in the front view, a maximum block height of 7.6 cm (3 in) height can be traversed without tipping the HLPR chair on its side. Hence, typical home doorway thresholds should not tip the HLPR Chair. Also, front to back, the HLPR Chair back wheel can be lifted approximately 12.4 cm (5 in) without tipping the chair.

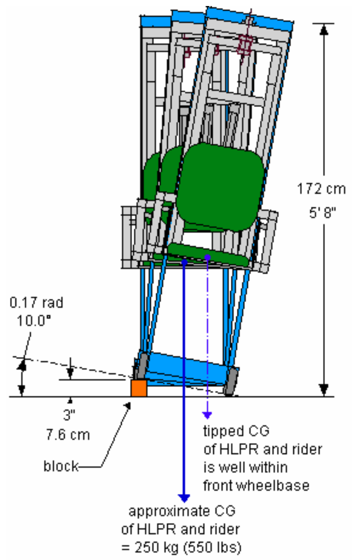
The HLPR Chair also has a vertical lift actuator to allow a patient to be raised approximately 0.9 m (36 in) above the mobility height configuration (see Figure 2 (c)). However, the HLPR Chair is not designed to be raised to its maximum height while on a sloped surface. Static, as well as Dynamic, Stability tests are planned in the near future with the HLPR Chair positioned at all possible heights in case this should occur.

IV. PLACEMENT ON OTHER SEATS

It is estimated that 1 in 3 nurses or caregivers will develop back injuries [9]. Most injuries occur because the patient is relatively heavy to lift and access to them is difficult when attempting to place the patient onto another seat. Some wheelchair dependents have difficulty transferring from their wheelchair to another seat without a caregiver’s help or other lift mechanisms. The HLPR Chair was designed with a patient lift and a rotary joint, along with a retractable seat, and footrest and torso lifts. Seat rotation about the patients’ center of gravity provides a simple means for the patient to be positioned above a toilet, seat or bed as depicted in Figure 4. The figure shows the concept of placing a patient onto (a) a toilet and (b) an armchair Also, Figure 4 (c) shows photographs of the HLPR Chair prototype in the rotated position and Figure 4 (d) shows it in the torso support position similar to Figure 4 (a) (center and right) graphic. Note that the dimension of the HLPR chair is slightly less in length when the seat is rotated and ready to place/pick-up a person onto/from another seat.



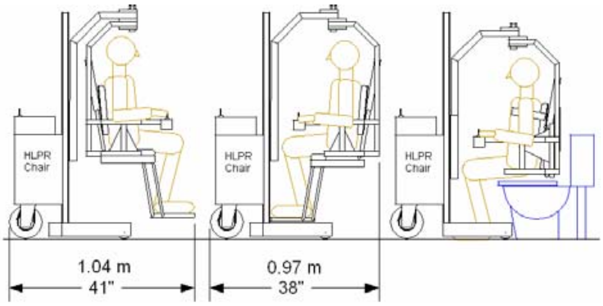
(a)



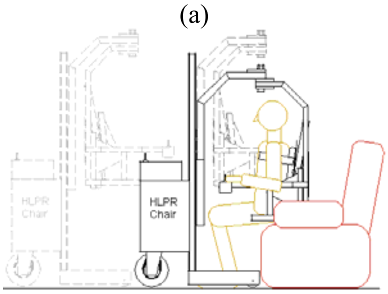
(b)

Figure 3 – Computer models of the HLPR Chair testing static stability of the (a) front and (b) side approximating maximum tipping angles for each.

Placing a person on a toilet has been explained in [16]. However, placing a person onto an armchair requires an additional maneuver. When the patient is brought to a soft cushion chair, as in Figure 4 (b), the chair compliance forces the persons’ weight to lower further into the chair cushion. Either the torso lifts lower the person the extra amount or the chair is lowered using the lift actuator. The current torso lifts function similar to patient crutches design. We plan to study softer patient lift methods based on inflatable cushions to provide lift and safe, soft padding for patient support.



(a)



(b)



(c) (d)

Figure 4 – Graphics of the HLPR Chair (a) approaching and placing a person on a toilet and showing length dimensions, and (b) placing of a person on a comfortable chair. Photographs of the HLPR Chair in the same positions as in the center (c) and right (d) graphic in (a).

For home use, the HLPR Chair is narrow enough to fit through typical doorways and openings. The turning radius of the HLPR Chair is approximately 76 cm (30 in). However, the HLPR Chair has a unique 'chair rotation within frame' design that, in many typical seat-access maneuvers, makes up for the longer turning radius. Figure 5 shows a top view drawing of a typical bathroom in a home.

In order to rotate the chair about the patient, it must be lifted above the cushion and patient legs. This is not a complicated maneuver, but it requires an additional step. Ideally, the patient is more comfortable for long periods of time on a soft chair than on the HLPR Chair or other rigid chair.

Once the person is placed on a toilet, the HLPR Chair can remain in the same position to continue supporting them from potential side, back or front fall. However, when placing a person onto a chair it could then be conceptually driven from the seat location, using radio frequency or through voice commands, to a charging or waiting location and out of the patients view. When requesting to be picked up again, the patient could conceptually call the HLPR Chair remotely and have it return to the same pick up location and reverse the seat placement procedure.

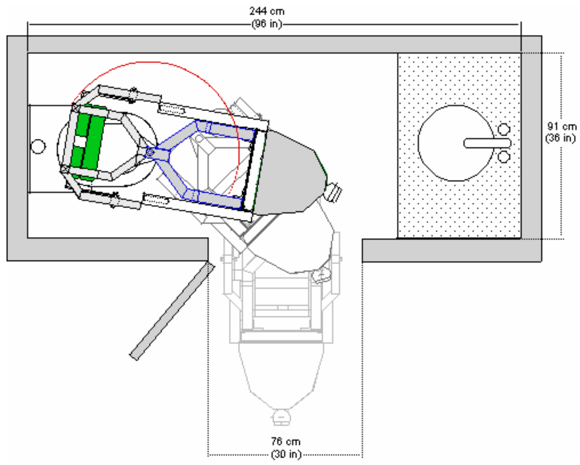


Figure 5 – CAD top view drawing of the HLPR Chair accessing a typical bathroom and toilet. The radius drawn is the area needed for the seat frame to rotate.

V. Towards Autonomous Control

The early HLPR Chair controls included only redundant manual joysticks and switches for both the rider (in the seat) and a caregiver (at the rear). The next goal of the NIST Healthcare Mobility Project will be to demonstrate autonomous navigation of the HLPR Chair further testing performance of an intelligent, lift-wheelchair system. The HLPR Chair will navigate into and through a toilet room and dock with a toilet [18]. NIST will perform 3D imaging and world modeling teaming with the University of Delaware to perform navigation control. Here we discuss how the HLPR Chair was modified and calibrated and discuss the plan to control it to achieve our goal.

A. HLPR Chair Modification and Plan

Recently, the HLPR Chair was modified (see Figure 6) to include encoders, attached between its frame and front caster wheels, a computer and computer interface electronics. The encoder design included adapting a shaft to one side of each caster wheel, passing it through a bearing attached to the frame and to an encoder. The encoders provide 3600 pulses per revolution allowing relatively fine measurement over a 12.7 cm (5 in) diameter caster wheel or approximately 90 pulses per centimeter (230 pulses per inch) of linear travel. The relatively high measurement accuracy of the wheels will support development of accurate path planning and control algorithms for the HLPR Chair.

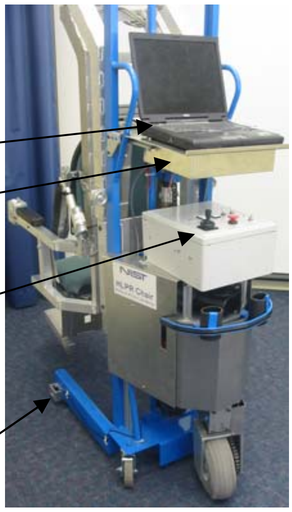


Figure 6 –HLPR Chair with recently added front wheel encoders, development computer and interface electronics, and advanced 3D imaging camera and color camera (cameras are shown in Figure 1).

Included in the "Nurse" control panel is a computer/manual switch. While switched in manual mode, all of the "Nurse" - labeled (rear) controls on the box or on the "Patient" - labeled (chair) can be used. While in computer control, drive and steer are controlled by an onboard computer. The computer is currently a personal computer (PC) laptop interfacing to off-the-shelf input/output (I/O) devices housed in the box beneath the PC and connected through a universal serial bus (USB) interface. This design was chosen as a simple developer interface to the HLPR Chair prototype knowing that the computer and its interfaces can be significantly reduced in size as future commercial versions are designed. Low level software drivers for the HLPR Chair drive and steer control were written in C++ under the Linux operating system.

B. Calibrating the HLPR Chair

In order to have reasonable wheel odometer accuracy, readings from various sensors must be calibrated against ground truth or accurate specifications. This section describes the calibration procedure used on the HLPR chair in preparation for autonomous control.

The drive wheel angle can be indirectly measured through the encoder speed when the vehicle is moving. When the vehicle is stationary, the angle can be determined by measuring the voltage across a steering angle potentiometer. However, in order to model a simple linear relationship one needs to collect corresponding pairs ($Ø_{min}$, v_{min}) and ($Ø_{max}$, v_{max}), where Ø is the drive-wheel angle and ν is the voltage across the potentiometer.

$$Ø(v) \approx [(v - v_{min}) / (v_{max} - v_{min})]\,(Ø_{max} - Ø_{min}) + Ø_{min} \quad (1)$$

Alternatively, one could be more accurate by fitting a least squares line through many data pairs. A simple linear least squares fit is used.

$$Ø(v) = p_0\, v + p_1 \quad (2)$$

$$\min_{p_0,\, p_1} \sum_{i=0} (Ø_i - (p_0\, v_i + p_1))^2 \quad (3)$$

The simple least squares method above is adequate for the data collected after some filtering to get rid of obvious outliers. The data collection process could be made automatic by programming the vehicle to drive in specific circles. This would need an open area to make sure the vehicle doesn't bump into objects while collecting data. Another safer approach is to manually drive the vehicle around, at different speeds and turning radii while the data collection is taking place. After the data has been collected, they can be analyzed and post-processed. A datum pair (Ø, ν) is good when all the following conditions are met:

1. The vehicle has been moving at a relatively constant speed for more than a 0.1 s duration (about 4 consecutive readings). The vehicle must be at steady state but not stationary.
2. Time elapsed must not be greater than 25 ms, this is to avoid any potential encoder overflow and thus bad angle measurements.
3. At least one encoder speed must exceed 0.14 m/s, since vehicle vibration causes noisy encoder readings up to that speed.

Figure 8 shows the collected data after retaining only good data and shows the least squares fit result. Line parameters can be extracted after doing a least squares fit on the good data. The equation for the line using the fitted parameters in Figure 8 is:

$$Ø(v) = -0.19555\, v - 0.054565 \quad (4)$$

C. Plans for Autonomous Control

The low level driver control and calibrated wheel odometers now allow for adding planned HLPR Chair navigation and obstacle avoidance control. NIST and the University of Delaware (UD) are teaming to use the NIST defacto standard software control architecture for intelligent machines called Four Dimensional/Real-time Control System (4D/RCS) and UD's robot behavior generation [18,19]. NIST has recently applied 4D/RCS to a Defense Advanced Research Project Agency (DARPA) Project called LAGR (Learning Applied to Ground Robots) [20].

The 4D/RCS structure developed for LAGR is shown in Figure 9. The basic premise of the 4D/RCS columns of boxes are to sense the environment around the robot (left column), to place the sensed information into a world model (middle column), and then plan and generate appropriate navigational paths and input these paths into the robot actuators in real time (right column). The horizontal rows of 4D/RCS boxes stack from a servo level control (bottom row) to grouped pixels, a lower resolution map, and a higher level planner (top row). The authors plan to adopt this control architecture on the HLPR Chair so that advanced 3D imagers, such as the one shown in Figure 1, and robust control algorithms can be “plug-and-played” to address the variety of patient mobility controls that may be needed.

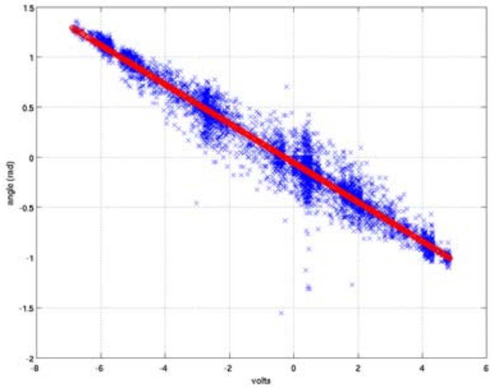


Figure 8 - Filtered data and its least squares fit using equation (4).

VI. Conclusions and Future Research

The HLPR Chair was designed to be a revolutionary patient lift and mobility system for wheelchair dependents, the elderly, stroke patients, and others desiring or requiring personal mobility and lift access. The system shows promise for moving these groups of patients into the work force and removing the burden placed on the healthcare industry. The system has been prototyped to show the basic concept of such a patient lift and mobility system. Further, recent CAD analysis of device stability shows this system as comparable to current wheelchairs when used inside the home on level surfaces. Future, planned stability tests will verify these CAD results. Also, the HLPR Chair was recently advanced by integrating a computer interface, wheel encoders and calibration providing a major step towards an autonomous demonstration partnering with the UD. The demonstration will prove a planned, near-term NIST 4D/RCS implementation while reaching the goal to navigate into a bathroom and dock with a toilet.

VII. Acknowledgments

The authors would like to thank Richard Simpson for his internal University of Pittsburgh, Human Engineering Research Laboratory report of current wheelchair and transfer patient statistical information.

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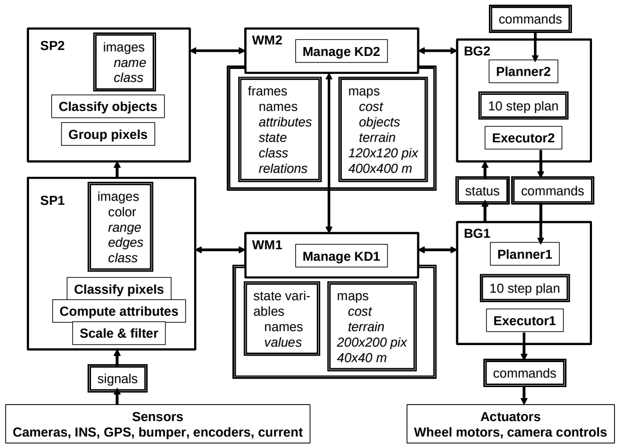

Figure 9 – NIST 4D/RCS 2-level, hierarchical control architecture developed for the DARPA LAGR Project and planned for implementation on the HLPR Chair.

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