1

Robotic Patient Lift and Transfer

Roger Bostelman and James Albus
National Institute of Standards and Technology
USA

1. Introduction

Pollack says "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." [Pollack, 2004] She follows by adding that this group is therefore subject to both physical and cognitive impairments more than younger people. These facts have a profound impact on how the world will keep the elderly independent as long as possible from caregivers. Both physical and cognitive diminishing abilities address the body and the mental process of knowing, including aspects such as awareness, perception, reasoning, intuition and judgment. Assistive technology for the mobility impaired includes the wheelchair, lift aids and other devices, all of which have been around for centuries. However, the patient typically or eventually requires assistance to use the device - whether to: push the wheelchair, to lift themselves from the bed to a chair or to the toilet, or guide the patient through cluttered areas. With fewer caregivers and more elderly in the near future, there is a need for improving these devices to provide them independent assistance. As further background, the authors have included sections on wheelchairs and lift devices.

1.1 Wheelchairs

Wheelchairs have been around for four hundred years since the first dedicated wheelchair, called an "invalids' chair," was invented for Phillip II of Spain. Later, in 1932, engineer Harry Jennings, built the first folding, tubular steel wheelchair similar to what is in use today. That chair was built for a paraplegic friend of Jennings named Herbert Everest. Together they founded Everest & Jennings. [Bellis, 2005]

There has been an increasing need for wheelchairs over time. In [Van der Woude, 1999] they state: "Mobility is fundamental to health, social integration and individual well-being of the human being. Henceforth, mobility must be viewed as being essential to the outcome of the rehabilitation process of wheelchair dependent persons and to the successful (re)integration into society and to a productive and active life. Many lower limb disabled subjects depend upon a wheelchair for their mobility. Estimated numbers for the Netherlands, Europe and USA are respectively 80,000, 2.5 million and 1.25 million wheelchair dependent individuals. These groups are large enough to allow a special research focus and conference activity. Both the quality of the wheelchair, the individual work capacity, the functionality of the wheelchair/user combination, and the effectiveness of the rehabilitation program do indeed determine the freedom of mobility. Their optimization is highly dependent upon a

continuous and high quality research effort, in combination with regular discussion and dissemination with practitioners."
There is also a need for smart wheelchairs as people are living longer than before, will typically become less mobile with time, and will have reduced cognitive abilities and yet will need and perhaps want to remain independent. With fewer, younger and more capable assistants available for these elders, it creates a need for personal robotic care. Standards are being set for these mobile devices including manual and powered devices. Intelligent powered chairs have not yet been standardized.

1.2 Patient lift

Just as important as wheelchairs are the lift devices and people who lift patients into wheelchairs and other seats, beds, automobiles, etc. The need for patient lift devices will also increase as generations get older. When considering if there is a need for patient lift devices, several references state the positive, for example:

- "The question is, what does it cost not to buy this equipmente A back injury can cost as much as f50,000, and that's not even including all the indirect costs. If a nursing home can buy these lifting devices for f1,000 to f2,000, and eliminate a back injury that costs tens of thousands of dollars, that's a good deal," [Marras, 1999]
- 1 in every 3 nurses become injured from the physical exertion put forth while moving non-ambulatory patients, costing their employers f35,000 per injured nurse. [Blevins, 2006]
- 1 in 2 non-ambulatory patients fall to the floor and become injured when being transferred from a bed to a wheelchair. - [US Bureau of Labor Statistics, 1994]
- "Nursing and personal care facilities are a growing industry where hazards are known and effective controls are available," said Occupational Safety and Health Administration (OSHA) Administrator John Henshaw. "The industry also ranks among the highest in terms of injuries and illnesses, with rates about 2 1/2 times that of all other general industries..." - [Henshaw, 2005]
- "Already today there are over 400,000 unfilled nursing positions causing healthcare providers across the country to close wings or risk negative outcomes. Over the coming years, the declining ratio of working age adults to elderly will further exacerbate the shortage. In 1950 there were 8 adults available to support each person who is sixty-five years of age and older, today the ratio is 5:1 and by 2020 the ratio will drop to 3 working age adults per elder person." [Wasatch Digital IQ, 2003]

1.3 Mobile patient lift devices

Toward full independence for wheelchair dependents (WCD's) and for elders, there is a need for patient lift devices to move them from one floor to the next, from the bed or chair to the toilet, to a wheelchair, to cars, and other places, etc. Combination lift devices and wheelchairs have become available within the past several years. They provide stair/curb climbing, lift to reach tall shelves, etc. Standards for lift wheelchairs have not yet become available.
Discussions with healthcare professionals and patients indicate that WCD's:

- want to be self-sufficient even in a typical home and remain at home (i.e., not in a medical care facility) throughout their life,
- and/or homeowners don't want the home changed due to costs and intrusive changes, or even radically exchanging homes (e.g., selling 2 level to buy a 1 level home),

- want to be mobile; pick from and place things on shelves and cabinets; be at eye level to others; sit in their favorite chair; use a standard toilet; perform household tasks (cook, clean, hobbies); and not rely on others for these tasks.

In our research, we also found that:

- wheelchairs/powered chairs mobilize but, typically cannot lift above 25 cm – 33 cm (10 in – 13 in).
- many wheelchairs/powered chairs cannot fit through standard bathroom doors.
- wheelchairs/powered chairs cannot typically place WCD's in favorite chairs, on toilets or on beds.
- gyro-stabilized lift chairs cannot lift typical patients to reach upper cabinet and shelf heights and are relatively expensive as compared to powered chairs,
- ceiling, patient, and other lifts do not have full user-controlled mobility and/or are usually location specific,
- there is a need for multiple devices for mobility and lift equating to more patient/insurance costs and providing cumbersome maneuverability for the patient,
- rehabilitation assistance is virtually non-existent when used with current wheelchairs aside from some basics in stander, walker, and rollator (rolling walker) technologies.
- Devices for wheelchair dependents and elderly:
  - Are need specific
  - Attempt to be very inexpensive
  - Are mostly available in care centers, hospitals
  - Typically require additional caregiver dependence.

Organizations studying wheelchair and patient lift devices are:

- Universities who perform intelligent wheelchair and wheelchair standards research
- Many companies who provide "need specific" devices

However, few devices if any, exist to provide generic or multi-purpose tools, for example: wheelchairs that lift AND navigate on their own AND support patient rehabilitation AND sense crosswalks AND sense negative obstacles (stairs) well before approaching them.

New to the patient mobility and lift device technologies are:

- Sensors that have advanced well beyond the still-used ultrasonic sensors.
- CSEM SR3000[1], Sick LMS, Canesta D200, PmdTech 3-dimensional imagers
- Computer systems that are much faster, smaller, and less-expensive than ever before
- Powered chairs that are off-the-shelf items now, where several companies sell them
- Intelligence algorithms that are just beginning to be integrated into powered chairs - e.g., through doorway navigation

Perhaps missing in current devices are improved standards that now exist only for manual and for some powered chairs. No standards exist for intelligent chairs that use advanced sensors, computers and actuation systems. We believe that before intelligent chairs are commercialized and sold to the general public, a target safety design standard should be in place. Advanced lift wheelchair devices could provide improved device capabilities such as:

- Safety: e.g., Powered chairs that don't require stair blocks or caregiver watch; guidance for blind riders

[1] The mention of specific products is for illustrative purposes only, and is not meant to imply that NIST recommends these products or to suggest that they are the best available.

- Obstacle detection and avoidance: e.g., know when operator is about to run into an obstacle; guidance for blind riders
- Reduced dependency on caregivers for the elderly and disabled

People that may benefit from lift-wheelchair standards, performance metrics and advanced technology are the:

- Elderly
- Wheelchair dependents
- Disabled persons
- Blind persons
- Nurses, Caregivers

This chapter will provide some examples of past and current wheelchair and patient lift technologies and provides an in-depth review of a new NIST concept called the "Home Lift, Position, and Rehabilitation (HLPR) Chair," including sections covering: the structure and mobility design, patient lift, placement on other seats, rehabilitation, and control. Modifications to the initial design towards ergonomics and manufacturability are discussed followed by conclusions, future research, and a list of references.

2. Current wheelchairs and patient lift devices

2.1 Wheelchair examples

Manual wheelchairs, like the example shown if Figure 1, are: portable as they can fold to a smaller size, are relatively lightweight as compared to powered wheelchairs, have been around for hundreds of years, and have become a pseudo-standard in hospitals, shopping malls, homes and many other facilities to assist immobile patients.

The concept of power assistance for a manual wheelchair is relatively new, and represents a viable alternative for individuals who are unable to generate sufficient propulsion force to use a manual wheelchair, but do not wish to use a traditional powered mobility device. In a power assisted manual wheelchair, the traditional rear wheel hubs are replaced with motorized hubs that serve to magnify or reduce (i.e., brake) the propulsive force applied to the rear wheels by the user. Power assistance is proposed as the basis for a Smart Power Assistance Module (SPAM) that provides independent mobility to non-ambulatory individuals with visual impairments. [Cooper, 2004]

Powered chairs have become readily available on the market today and are made by several companies. These devices allow the operator to control their mobility without exerting manual force to move them and the device. Using one's arms to push a manual wheelchair can result in injuries, the need for surgery, and potential loss of independent mobility. Powered chairs can help eliminate these issues. Powered chairs are also being designed for sit-to-stand capability as shown in Figure 1 (center). This allows the patient to exert forces on the legs if possible and to reach items on shelves that are difficult for non-lift wheelchairs to access. Figure 1 (right) shows a gyro-stabilized lift wheelchair that allows a patient to be rolled up and over curbs and lifted relative to some cabinet heights and eye level to average-heights of standing persons.

It is however, important to note the need for operator attention while driving powered scooters or chairs. One of the authors personally watched an elderly person, who recently suffered from a stroke, driving a scooter while being inattentive to his surroundings inside a store. As a result, several times the elderly driver crashed into store displays, shelving and other people. This dangerous situation begs for assistance from a caregiver to manually push this person around using a manual wheelchair. Alternatively, the powered chair could be equipped with advanced operator attention control interlocked to the low level mobility power to cut-off power to the drive system when the operator is inattentive.

Fig. 1. (left to right) Manual Wheelchair, Powered Chair with patient sit-to-stand lift, Gyro-Stabilized Lift Wheelchair

2.2 Patient lift device examples

The Patient Pivot shown in Figure 2 allows a person to be lifted from a seated position, once strapped to the Pivot, and rotated forward to allow patient placement on another seat. The rotate mechanism uses levers allowing the caregiver to supply reduced force relative to lifting without the device.

Once a sling or hammock sheet is placed beneath the patient, lift devices such as the Hoyer and Patient lifts shown in Figure 2 can be used to power lift the patient from a seated or lying position. The device allows compliance for rotating the patient about the lift point and is manually mobilized by the caregiver. The Patient lift can reach the floor for patients who have fallen or can lift from seats or beds using straps attached to the device (not shown). This device also allows the device legs to be power separated for easy patient access to the device and/or to accommodate access to wide-base seats.

Fig. 2. (left to right) Patient Pivot, Hoyer lift with patient in a sling, and Patient lift

Wall or ceiling mounted patient lift devices (see Figure 3) provide lift and mobility from, for example a bed to a wheelchair. The sling or harness is required to surround the patient and therefore, must be initially placed beneath the patient and attached to the ceiling lift.
These lift devices have two degrees of freedom allowing lift of a harnessed patient in a sling like a crane and rotation about a horizontal pivot mounted to the wall or other support frame, such as a bed.

Fig. 3. Wall (left) and Ceiling (right) Mounted Patient Lift Devices

2.3 Patient transfer device examples

Some automobile and truck manufacturers have begun to develop transfer mechanisms built into the seat to allow access by the disabled. The chairs, made of actual car seats, are lifted and placed on the ground or into the vehicle.
Towards a home patient transfer concept, the Korea Advanced Institute of Science and Technology (KAIST) developed a system to transfer a person from a bed to a robotic wheelchair without assistance of another person in their Intelligent Sweet Home. [Park, et. al. 2007] The robotic wheelchair was equipped with autonomous mobility including: sensing, localization, obstacle detection, and motor control. The ultimate goal of a robotic wheelchair is to take the user automatically and safely to the destination.
For accomplishing the patient transfer objective, the robotic wheelchair moves autonomously to the predefined docking ready position and performs docking with the robotic transfer system. During the docking operation, bumpers of the robotic wheelchair detect collisions with the robotic transfer system and help make docking safe. Figure 4 shows the robotic wheelchair moving toward to the patient suspended in the patient lift. During autonomous moving, the robotic wheelchair performed localization, object detection, and motor control tasks.
The patient mobility, lift, and combinations of mobility and lift device examples cited above demonstrate that there are organizations who are or have recently been actively developing technology to transfer patients. What is missing is a single compact device to be used in a medical or caregiver facility and eventually the home that can independently:

- provide powered mobility for a patient,

- and lift them to reach from the floor to the ceiling or highest cabinets and shelves,
- and place the patient on a chair, bed or toilet
- and even provide some rehabilitation.

Built-in device intelligence is also required for patients who are not cognitively able to control the device for performing daily tasks.

Fig. 4. (left) Autonomous moving to the predefined position, (right) Docking operation

3. Home lift, position, and rehabilitation (HLPR) chair

In 2005, the National Institute of Standards and Technology's (NIST) Intelligent Systems Division (ISD) began the Healthcare Mobility Project to address the staggering healthcare issue of patient lift and mobility. ISD researchers reviewed currently available technology through a survey of patient lift and mobility devices [Bostelman & Albus 2006-1]. The example cited above and many others are shown in this report. The report exposed a need for technology that includes mobility devices that can also lift and maneuver patients to other seats and technology that can provide for rehabilitation in the home to help the patient become independent of the wheelchair.

An additional area investigated in the survey was intelligent wheelchairs. NIST has been studying intelligent mobility for the military, transportation, and the manufacturing industry for at least 20 years through the Intelligent Control of Mobility Systems (ICMS) Program. [NIST, 2000] NIST is researching a standard control system architecture and advanced 3D imaging technologies within the ICMS Program. The NIST Healthcare Mobility Project is then applying them to intelligent wheelchairs where NIST has begun outfitting the HLPR Chair with computer controls. Although throughout the world there are or have been many research efforts in intelligent wheelchairs, including: [Kuno, et. al. 2000; Patel, et. al. 2002; Song et. al. 1999; Yanco, et. al. 1995] 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.

3.1 HLPR chair design

The HLPR Chair [Bostelman & Albus 2006-2] prototype, shown in Figure 5, 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 measures 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 bathroom doors. The HLPR Chair frame could be made lighter with aluminum instead of steel.

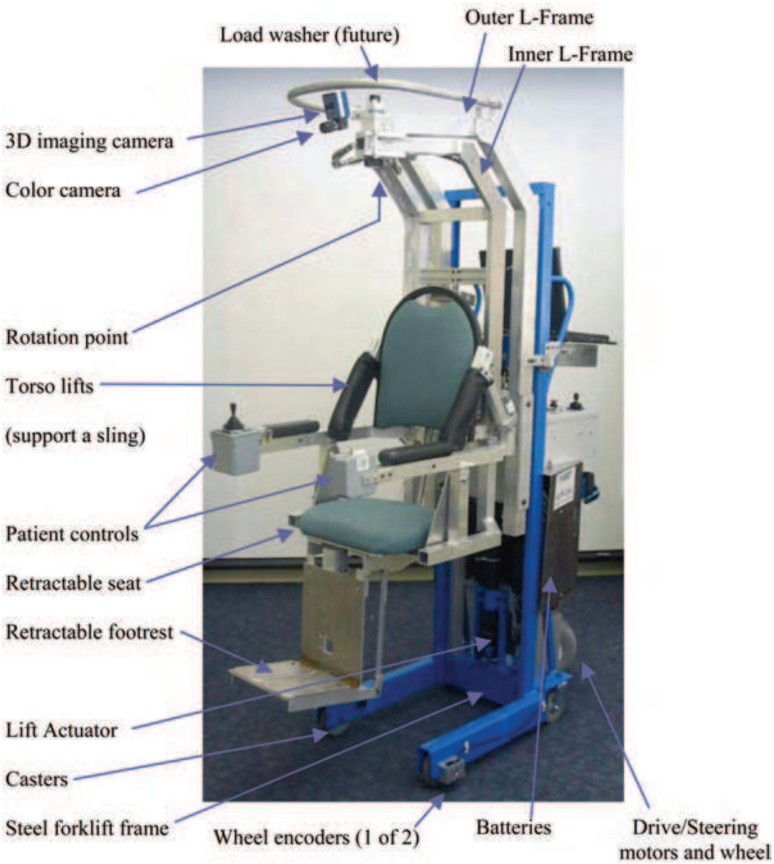


Fig. 5. The HLPR Chair prototype.

The patient seat/stand mechanism is a double, nested and inverted L-shape 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 photograph. 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 Figure 5. The frames rotation point is above the casters at the very front of the HLPR Chair frame to allow access outside the wheelbase when the seat is rotated π rad (180°) and is the main reason access to other seats is available. 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 π rad (180°) with a 136 kg (300 Lb) 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 on the market. 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 provide for a more vertical and compact drive system design. The drive motor is mounted perpendicular to the floor and above the drive wheel with chain drive to it. The steering motor is coupled to an end cap on the drive motor and provides approximately π rad (180°) rotation of the drive wheel to steer the HLPR Chair. The front of the robot has two casters mounted to a Ushaped frame.

The prototype high-speed drive motor is geared down through a chain-drive providing HLPR Chair speeds up to 0.7 m/s (27 in/s). Also, the drive amplifier gain has been adjusted to provide sufficient speed for typical eldercare needs and can be readjusted to allow for higher speeds as desired.

Steering is a novel single wheel design hard stopping the wheel at just beyond π rad (180°) 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 steering rotation amount can be limited by reducing the amount of drive speed when large steering angles are commanded so as not to roll the frame during excessive speed. 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.

For access to the HLPR Chair and for mobility, the HLPR Chair seat is lowered as shown in Figure 6. 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. Also, manually rotated feet pads can be deployed to provide a wider footrest. When retracted, the footrest pads automatically rotate within the footrest volume.

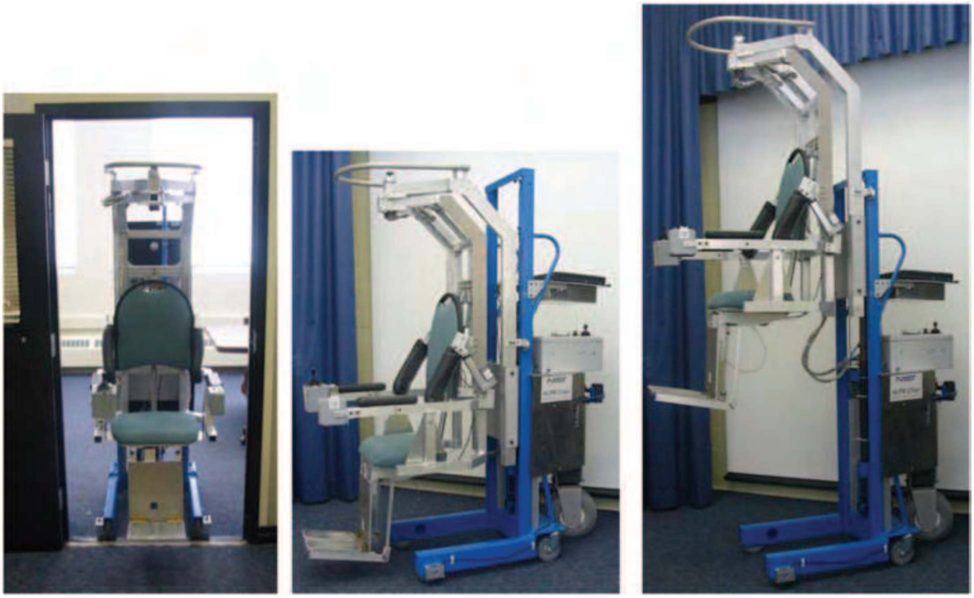


Fig. 6. The HLPR Chair in the mobility configuration showing the front view relative to a typical doorway (left), the side view (center) and the patient lift position (right).

3.2 Patient lift

Patient lift capability is designed into the HLPR Chair to allow user access to high shelves or other tall objects while seated. The HLPR Chairs' patient lift (see Figure 6 - right) is approximately 1 m (36 in) to reach what a typical, standing 2 m (6 ft) tall person could reach. This is a distinct advantage over marketed chairs and other concepts. [Bostelman & Albus 2006]. The additional height comes at no additional cost of frame and only minimally for actuator cost.

Lift is achieved by a 227 kg (500 Lbs) max. lift actuator that can support 681 (1500 Lbs) statically on the HLPR Chair prototype. The actuator can be replaced with a higher capacity unit if needed. The actuator connects to a lift plate with a steel chain that is fixed to one end of the HLPR Chair frame and to the lift plate at the other end. The actuator pushes up on a sprocket of which the chain rolls over providing 0.9 m (36 in) lift with only a 0.45 m (18 in) stroke actuator. The outer L-frame is then bolted to the lift plate. Rollers mounted to the lift plate roll inside the HLPR Chair vertical C-channel frame.

3.3 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. Wheelchair dependents have difficulty moving from a seat, to their wheelchair and back without a caregivers help or other lift mechanisms. The HLPR Chair was designed with the patient lift, as explained previously, to not only access tall objects, but to also pick up and place the patient in other chairs, on toilets, and on beds.

Figure 7 shows the concept of placing a patient onto a toilet. Figure 8 (left) shows the HLPR Chair prototype in the rotated position and Figure 8 (right) shows it in the torso support position similar to the Figure 7 (center and right) graphic.

To place a HLPR Chair user on another seat, they drive themselves to, for example, a toilet, seat, or bed. Once there, the HLPR Chair rotates the footrest up and beneath the seat and the

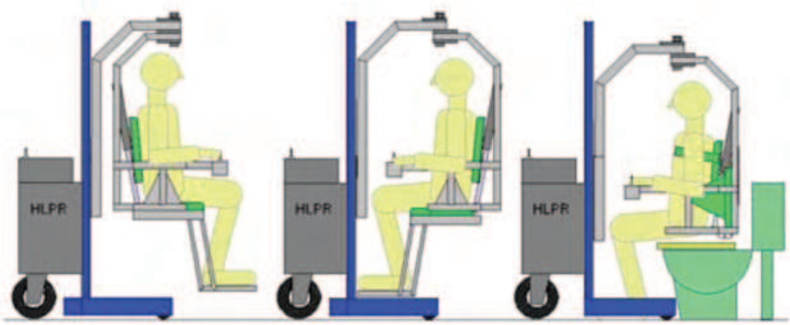


Fig. 7. Graphic showing the concept of placing a patient onto a toilet or chair with the HLPR Chair. The patient drives to the target seat (left), manually rotates near or over the seat (middle) while the torso lifts support the patient and the seat retracts, and then is lowered onto the seat - toilet, chair or bed (right).

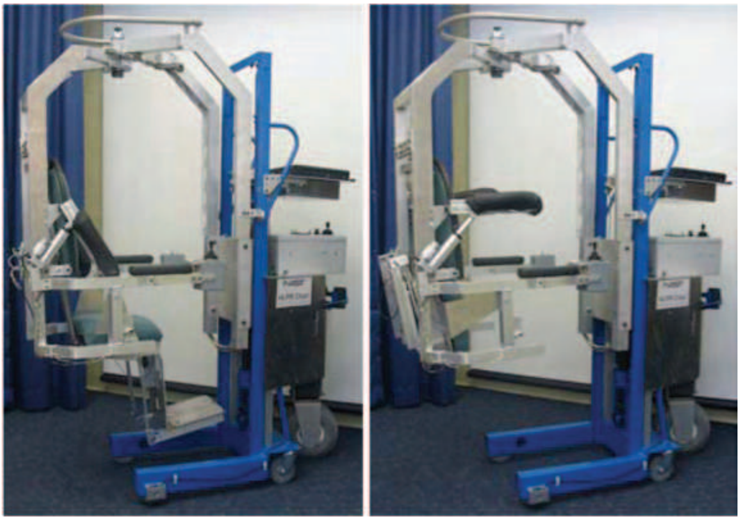


Fig. 8. The HLPR Chair in the same positions as in the center and right Figure 7 graphics placing a person on another seat.

patients feet are placed on the floor personally or by a caregiver. The HLPR Chair inner Lframe can then be rotated manually with respect to the chair frame allowing the patient to be above the toilet. Padded torso lifts, similar to crutches, then lift the patient from beneath his/her arm joints. The seat, with the footrest beneath, then rotates from horizontal to vertical behind the patients back clearing the area beneath the patient to be placed on the toilet, seat, bed, etc.

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, the HLPR Chair must lift the patient and the patient manually rotates the chair from around the patient and out of the patients space. The HLPR Chair could then conceptually be 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.

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 9 shows a CAD top view drawing of a typical bathroom in a home.

To place a patient onto, for example, a very soft sofa requires a simple, additional step not explained above. In order to rotate the chair about the patient once they have been seated on the sofa, it must first be lifted above the cushion and patients legs. Ideally, the patient is more comfortable on this type of seat than on the HLPR Chair or on a rigid chair. Once the person is placed on a , the HLPR Chair can remain in the same position to continue supporting the patient reducing potential for falling to the side, back or forward.

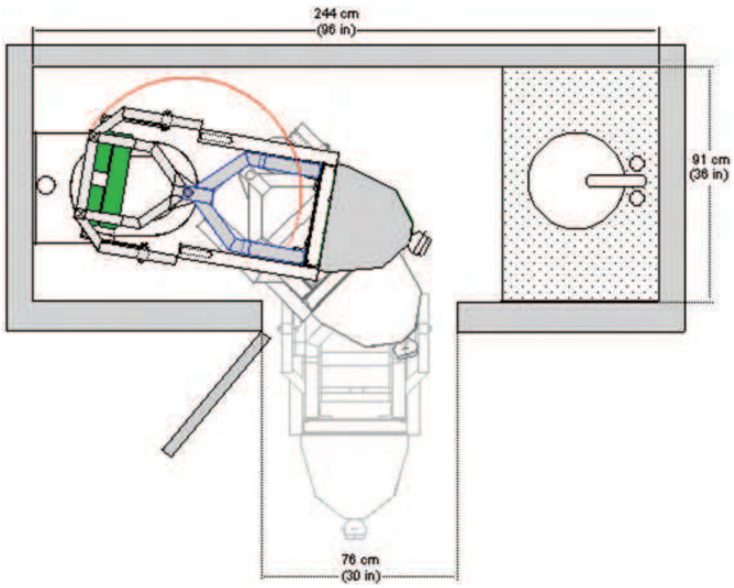


Fig. 9. CAD top view drawing of the HLPR Chair accessing a typical bathroom and toilet. The radius drawn is the area needed for the seat frame to rotate.

3.4 Manual control

The HLPR Chair controls include a joystick that sends drive controls to power amplifiers that control the drive and steering. The patient lift actuator is also controlled with the same type power amplifier through a rocker switch. A lever switch is used to control seat and footrest retraction or deployment.

The footrest, seat and torso lift actuators are direct powered switched forward and reverse from the battery through momentary rocker switches. Actuators for the footrest and each torso lift has 8cm (3 in) stroke while the seat includes a 31 cm (12 in) actuator to rotate it from seated position to behind the back and vice versa.

Behind the seat and frame and above the drive/steer wheel is the electronics box that houses the controls for the HLPR Chair while also providing a “Nurse” or caregiver control panel that duplicates the patient controls at the seat. The Nurse control panel (see Figure 10) includes all the control functions for a nurse or caregiver to drive or lift a dependent patient. Control redundancy is designed into the HLPR Chair to also allow a caregiver to quickly gain control of the device as needed. A “Nurse/Patient” switch on the Nurse control panel allows switching between the rear (Nurse) controls and the chair (Patient) controls.

3.5 Towards autonomous control

The HLPR Chair was recently modified (see Figure 10) 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. Although the encoder and housing add an additional 2.5 cm (1 in) to each side of the base, the overall HLPR Chair base width is still within the chair-frame width and therefore, within the overall HLPR Chair width of 58 cm (23 in). 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/cm (230 pulses/in) 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.

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 interfaced 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.

Software drivers for the HLPR Chair drive and steer control were written in C++ under the Linux operating system.

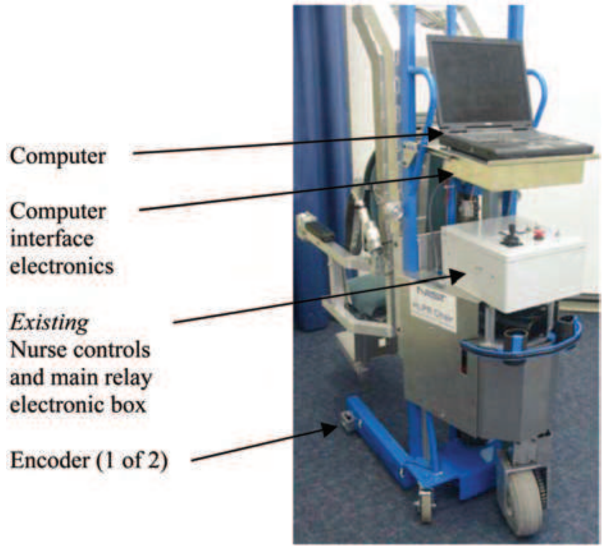


Fig. 10. The HLPR Chair with recently added front wheel encoders, development computer and interface electronics. Recently added advanced 3D imaging camera and color camera are shown in Figure 5.

This low level control is now ready to add planned HLPR Chair navigation and obstacle avoidance control. NIST and the University of Delaware (UD) are teaming to use the NIST standard software control architecture for intelligent machines called 4 Dimensional/ Real-time Control System (4D/RCS) and UD's robot behavior generation. [Sira-Ramirez & Agrawal, 2004] NIST has recently applied 4D/RCS to a Defense Advanced Research Project Agency (DARPA) Project called Learning Applied to Ground Robots (LAGR). [Albus, et al. 2006] The 4D/RCS structure developed for LAGR is shown in Figure 11. 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), 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 standard control architecture on the HLPR Chair so that advanced 3D imagers, such as the ones shown in figure 5, and robust control algorithms can be "plug-and-played" to address the variety of patient mobility controls that may be needed. An earlier version (from the one pictured in figure 5), 3D imaging camera was mounted on an early version of the HLPR Chair and a control algorithm was developed and tested. Results of this test, as explained in [Bostelman, et. al. 2006], clearly show detected obstacles in the vehicle path and a planned path around the obstacles.

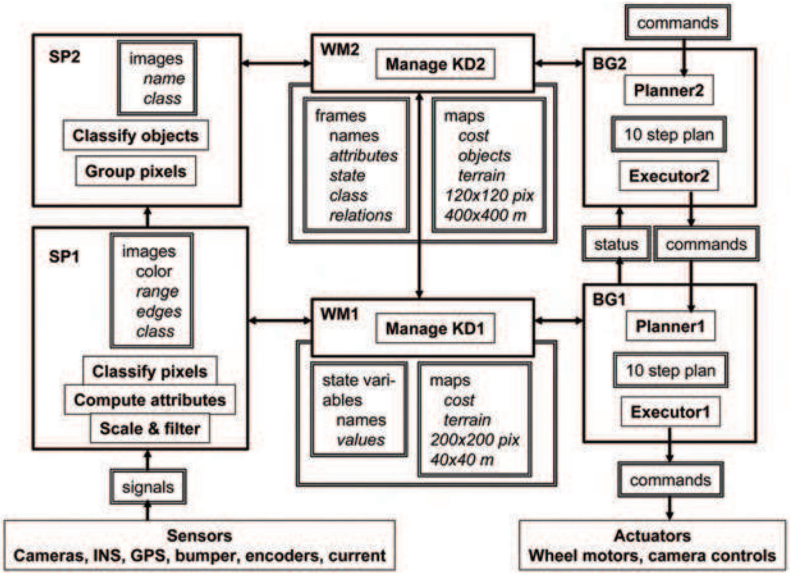


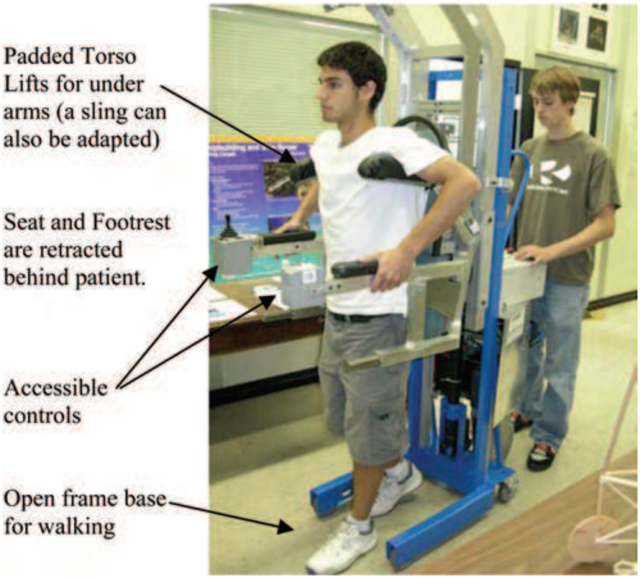
Fig. 11. NIST 4D/RCS 2-level, hierarchical control architecture developed for the DARPA LAGR Project and planned for implementation on the HLPR Chair.

3.6 Patient rehabilitation

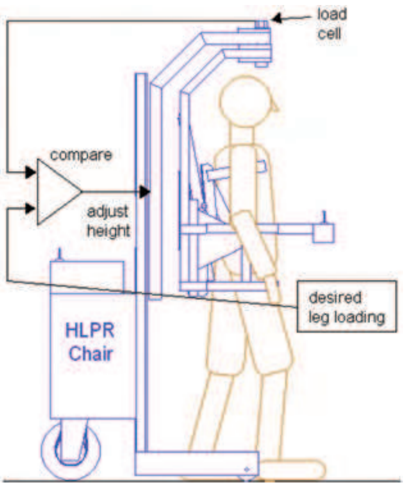
HLPR Chair enhances patient rehabilitation through a load sensor and control on the lift actuator, as described in [Banala, et. al. 2007]. The authors designed rehabilitation into the HLPR Chair to allow, for example, stroke patients to keep their legs active without supporting the entire load of the patients body weight. The patient, once lifted, could walk while supported by the HLPR Chair driving at a slow walking pace towards regaining leg control and perhaps eliminating the need for a wheelchair.

To accomplish rehabilitation, the HLPR Chair includes, as explained in the Placement on Other Seats section, footrest and seat rotate behind the patient while he/she is lifted with torso lifts. However, instead of being placed low on a seat, the patient lift continues to mov up lifting the patient as they move their legs beneath them to standing position. The HLPR

Chair's open U-frame base allows access to the floor directly beneath the patient for standing. Figure 12 shows a photograph of the prototype in this configuration and a concept of how the HLPR Chair can be used for patient rehabilitation.



(a)



(b)

Fig. 12. (a) The HLPR Chair prototype in the rehabilitation/walking configuration. Summer Interns (Alex Page and Robert Vlacich) demonstrate the patient and nurse configuration as part of their official duties. (b) Graphic showing the concept of how the HLPR Chair can be used for patient rehabilitation and incorporate future legs load control.

Additionally, the patient can be continuously monitored with a load sensor at the L-frames rotation point. The patient could adjust the amount of load he/she wishes to place onto their legs and on the floor by rotating a dial on the controls from 0% to 100%. Load control is a future concept to be applied to the HLPR Chair prototype in the next several months.

4. Improved HLPR chair ergonomics and manufacturability

Modifications have continued on the HLPR Chair targeting more ergonomic designs, less expensive manufacturability, and a more load-distributed patient support while being transferred to other seats or in the standing position. The more ergonomic design and less expensive manufacturability were achieved by using a bent tubing design for the seat and base frames. Thin wall, 3.2 mm (0.125 in) wall thickness, tubing was bent into the curved shape as shown in Figure 13. Also shown in Figure 14 is the seat frame designed to be wider as compared to the first HLPR Chair design shown in figure 5, as well as being curved similar to the new base frame design. The wider frame allows standard, off the shelf seats to be used on the HLPR Chair. To allow very low friction and hollow rotary joint design for electrical cable harnessing, a thin, inexpensive bearing was used between the frames allowing a very smooth, low side-to-side torque design. These two designs were an order of magnitude decrease in manufacturability cost from the previous design.

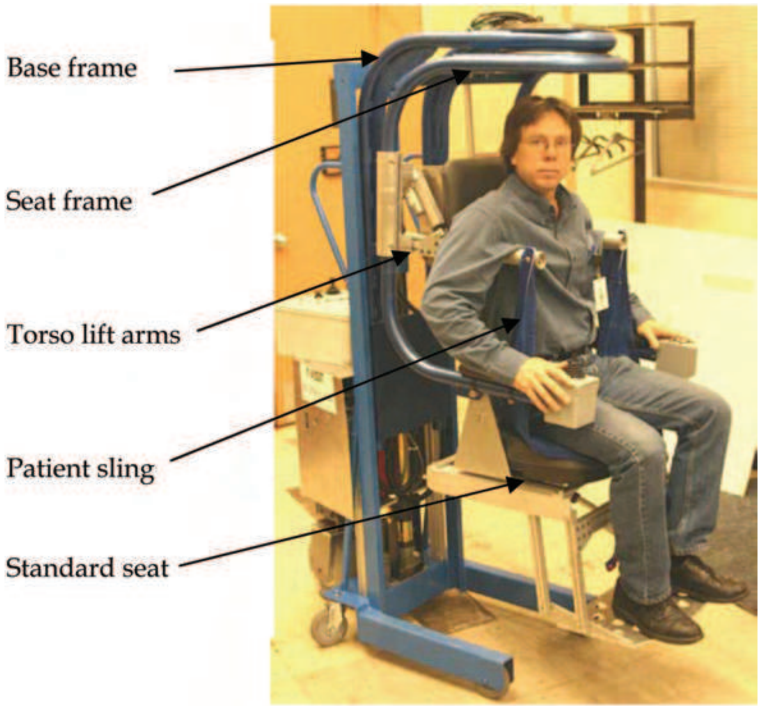


Fig. 13. The modified base and seat frames of the HLPR Chair from the previous welded design.

To address the more load-distributed patient support need when patients are transferred to other seats or in the standing position, a modified sling design was used (see Figure 14). The modified sling combines a typical medical sling and climbers harness but, uses much less material. The same torso lifts are used as in the previous design although they now do not provide the patient lift. They are simply used as a lift mechanism for the sling which now lifts the patients legs and buttocks. The original torso lift arms now only provide a sense of security to the patient without causing underarm injury as may have been experienced with only using torso lift arms as in the previous design shown in Figure 5. A standing position sling is also planned for integration with the HLPR Chair. The design will be slightly different from the seated sling design since it will include an off-the-shelf climbers or rehabilitation harness modified to fit the HLPR Chair and suspended from above the patient.

Fig. 14. Photographs of the HLPR Chair sling showing (left) the sling ready for the patient to be seated, (center) a patient with the sling ready to lift while seated on the HLPR Chair seat, and (right) the patient fully supported by the sling with the HLPR Chair seat rotated behind the patient.

5. Conclusions and future research

There have been many patient transfer devices designed and developed over many years. 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 even 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. The HLPR Chair was built to demonstrate its relatively inexpensive capabilities to the healthcare industry and to demonstrate potential, near-term capabilities with robust controls for mobility and rehabilitation.

Autonomous mobility control using the 4D/RCS standard control architecture and integration of advanced 3D imagers is planned for a next step through teaming with the University of Delaware under a federal grant. Force loading for rehabilitation of patient legs will also be studied in the near term.
Ergonomics and manufacturability of devices such as the HLPR Chair are critical for the general public and manufacturers to accept an appealing, safe and low cost patient transfer design.
Commercialization is now being considered by the healthcare industry. Figure 15 shows concept drawings developed by Innova Robotics and Automation, Inc. of a more ergonomic and commercialized version of the HLPR Chair. Collaborations for proving the service capabilities and evaluating performance of commercial versions of the HLPR Chair and also, setting safety and performance standards for this type of assist device are being pursued and expected in the near future.

Fig. 15. Front (left) and rear (right) concept drawings of the HLPR Chair as a more ergonomic and commercialized version.

6. References

Albus, J., Bostelman, R., Hong, T., Chang, T., Shackleford, W. & Shneier, M. (2006). *Integrating Learning into a Hierarchical Vehicle Control System*, Integrated Computer-Aided Engineering Journal.

Banala, S., Agrawal, S., Fattah, A., Scholz, J., Krishnamoorthy, V., Rudolph, K., & Hsu, W-L. (2007). *Gravity Balancing Leg Orthosis and its Performance Evaluation*, IEEE Transactions of Robotics.

Bellis, M. (2005). “Wheelchair History,” *http://inventors.about.com/library/inventors/* blwheelchair.htm

Blevins Medical, Inc. (2006). Healthcare Statistics: http://www.patientlift.net/ 282164.html.

Bostelman, R. & Albus, J. (2006-1). Survey of Patient Mobility and Lift Technologies Toward Advancements and Standards, NISTIR u7384.

Bostelman, R &, Albus, J. (2006-2). HLPR Chair – A Service Robot for the Healthcare Industry, 3rd International Workshop on Advances in Service Robotics, Vienna, Austria.

Bostelman, R., Russo, P., Albus, J., Hong., T., & Madhavan, R. (2006). Applications of a 3D Camera Towards Healthcare Mobility Aids, IEEE International Conference on Networking, Sensing and Control, Ft. Lauderdale, FL, April.

Cooper, R., Simpson, R., LoPresti, E., Guo, S. & Ding, D. (2004). NIH – Small Business Innovative Research Project, http://www.herlpitt.org/research.htm.

Dictionary.com (2007).

Henshaw, J. (2005). *http://www.osha.gov/SLTC/nursinghome/solutions.html*, Occupational Safety and Health Administration.

Kuno, Y., Murashima, T., Shimada, N. & Shirai, Y. (2000). Intelligent Wheelchair Remotely Controlled by Interactive Gestures, International Conference on Pattern Recognition, vol. 04, no. 4, p. 4672.

Marras, W. (1999). Lifting Patients Poses High Risk for Back Injuries, Ohio State University, http://researchnews.osu.edu/archive/resthome.htm.

NIST Intelligent Control of Mobility Systems Program website (2007). http://www.isd.mel.nist.gov/ researchvareas/mobility/index.htm.

Park, K., Bien, w., Lee, J., et. al. (2007). *Robotic Smart House to Assist People With Movement Disabilities*, Autonomous Robots Journal, V. 22, Iss. 2, Ppg. 183-198.

Patel, S., Jung, S-H., Ostrowski, J., Rao, R. & Taylor, C. (2002). Sensor based door navigation for a nonholonomic vehicle, GRASP Laboratory, University of Pennsylvania, Proceedings IEEE International Conference on Robotics and Automation, Washington, DC.

Pollack, M. (2004). Intelligent Technology for Adaptive Aging Presentation, AAAI-04 American Association for Artificial Intelligence Conference Keynote Address, 2004

Sira-Ramirez, H., Agrawal, S. (2004). Differentially Flat Systems, Marcel Dekker (Control Engineering Series), Hardbound, ISBN 0-8247-5470-0, 467 pages.

Song W., Lee, H., Bien, w. (1999). “KAIST - KARES: Intelligent wheelchair-mounted robotic arm system using vision and force sensor, Robotics and Autonomous Systems, vol. 28, no. 1, pp. 83-94(12), 31, Publisher: Elsevier Science.

U.S. Bureau of Labor Statistics (1994). from Blevins website: http://www.patientlift.net/ 282164.html.

Van der Woude, L., Hopman, M., & Van Kemenade C., (1999). *Biomedical Aspects of Manual Wheelchair Propulsion: The State of the Art))*, Volume 5, Assistive Technology Research Series, 392 pp., hardcover

Wasatch Digital iQ. (2003) “InTouch Healthxs Remote Presence Robot Used by Healthcare Experts,” http://www.wasatchdigitaliq.com/parser.phpenavyarticle&articlevidy 43, Santa Barbara, CA & Salt Lake City --(Business Wire).

Yanco, H., Hazel, A., Peacock, A., Smith, S. & Wintermute, H. (1995). Initial Report on Wheelesley: A Robotic Wheelchair System, Department of Computer Science, Wellesley College.