Design and usability of the PURE ballbot wheelchair

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INTRODUCTION

The World Health Organization reports that ~65 M people are in need of a wheelchair [1]. The 2010 US Census indicated 3.6 M wheelchair users (WCU) over the age of 15 [2]. The majority being manual WCU (mWCU) [3]. Long-term overuse upper extremity injuries have been identified in over 70% of mWCU (e.g., [4]. To effectively and efficiently propel a manual wheelchair, the user needs both hands, which compromises life experiences of mWCU due to inability to grasp and carry objects or hold another person's hand during propulsion [5]. The design of the traditional mWC, which is essentially a chair supported between two large drive wheels with front casters, has not changed since the first patents awarded in the 1890s [6]. This design has further limitations that impact the user's life experiences including high risk of falling on uneven terrain with small obstacles, and inaccessibility to a variety of terrains (gravel, grass, sand, snow) and tight spaces (restroom stalls, airplane aisles). Powered wheelchairs address some limitations of mWC, as they operate with one-hand via a joystick and are more stable over small obstacles. Most WCU with sufficient upper limb functionality will not use powered wheelchairs due to their substantial weight (22.6 to 113 kg), runtime limitation (11 to 32 km), larger size, and greater cost. Weight, footprint, and design may render these devices useless in tight spaces and add complexity to transportation due to their need for a lift-equipped vehicle.

Self-balancing mobile robots with two coaxial wheels were inspired by the classic toy problem of balancing an inverted pendulum with a motorized cart (e.g., [7,8]). The first consumer-level two-wheeled self-balancing mobility device, iBOT wheelchair, was developed by DEKA and sold in the early 2000s and reintroduced in 2019 by Mobius Mobility. This self-balancing technology was then used in DEKA's Segway Human Transporter released in early-2000 [9]. Lean-to-steer was later added where users control forward or backward motion by weight shifting in the desired direction and control turning via a handle. Self-balancing designs have been marketed in two-wheeled powered wheelchairs (e.g., [10,11]. These devices are controlled by a handlebar or joystick, and/or trunk movements for users who possess higher functional ability. Most suffer from bulky size and heavy weight (18 to 91 kg).

A more advanced type of self-balancing mobile robot has been developed, a.k.a. the *ballbot* (e.g, [12,13]. Instead of using two coaxial wheels, this robot rides on top of a ball or "spherical wheel" and is capable of moving in any direction, or "omnidirectional" movement. The most popular ballbot design utilizes a drivetrain composed of omniwheels, motors, and a ball [13]. The omniwheel can roll forward like a normal wheel, but can also slide sideways with minimal friction due to the addition of small rollers mounted perpendicular to the main rotation axis.

A disruptive approach for achieving rolling mobility of people with lower-limb disability is needed. We are breaking the mold of the traditional wheelchair through exploration of a safe, compact, adaptive ballbot, where the rider sits on a sleek modular mobility device and navigates via only upper-body movements (leaning and twisting). Our interdisciplinary team of designers, disability specialists, and engineers worked alongside WCUs to develop a novel device that can afford mWCUs the opportunity to move around their environment hands-free, i.e., PURE (Personalized Unique Rolling Experience).

PURE'S KEY FEATURES

PURE provides completely hands-free control for different driving modes (Steer, Slide, Spin). Steer operates similar to a standard vehicle: forward, backward, turning. Slide translates the device sideways like a rolling office chair (a unique feature of omnidirectional movement). Spin allows rotating 360° upon a fixed point. The rider seamlessly transitions between modes by just leaning and/or twisting the torso. The rider increases speed by leaning further and stops by leaning back.

Due to the sleek design of the ballbot architecture, PURE has a minimal footprint no larger than the user's hips while seated (0.4 m × 0.4 m). Being smaller than a manual wheelchair, it can provide access to smaller spaces such as inaccessible public restroom stalls.

DESIGN

PURE has three main subsystems (Figures 1 and 2). 1) The ballbot drivetrain which manages system balance and velocity tracking. 2) The Torso-dynamics Estimation System (TES) that measures the rider's torso movements and later maps them into velocity control signals. 3) The shared control vision-guided perception system for advanced driver assistance control that ensures environmental awareness and collision prevention.

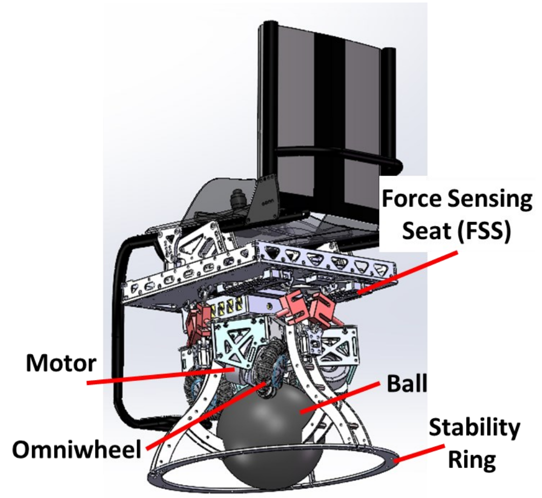

Figure 1. PURE's ballbot drivetrain and Torso-dynamics Estimation System (TES). The TES is composed of the Force Sensing Seat (FSS) and a small IMU on rider's chest (not shown)

Drivetrain: The drivetrain consists of a ball, a set of three omniwheels and motors, electronics, batteries, sensors, and structural elements, including ball arrestors to secure the ball against the omniwheels and a stability ring to minimize loss of balance or falling due to extreme tipping [14]. Customized Quasi-Direct-Drive Brushless DC motors were attached to single-plate omniwheels with thermoplastic polyurethane (TPU) rollers. We fabricated our own spherical wheels using bowling balls covered with various materials (SBR rubber, TPU, polyurethane (PU). A cascaded linear quadratic regulator and proportional-integral (LQR-PI) controller is used for balancing and maneuvering. This embodiment weighs 37 kg and can carry up to 60 kg, turn 180° within 1 s, move at a maximum speed of 2.4 m/s, roll over raised surfaces at least 3.1 cm, go up US ADA-compliant ramps (1:12 maximum slope), and operate for ~2 hours before recharging.

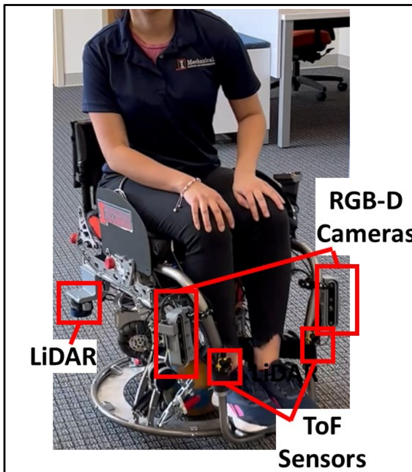

Figure 2. Vision system for driver assistance

Torso-dynamics Estimation System (TES): The TES uses a Force Sensing Seat (FSS) with six uniaxial load cells for rider-seat interaction torque (translational) measurement and a chest-mounted inertial measurement unit (IMU) for torso twist (yaw) detection [15]. An admittance controller maps these signals to PURE's velocity commands for the drivetrain. The controller is designed with user-selected adjustable sensitivity to respond to the upper body movements of even the least functional paraplegic, i.e., those with limited to no trunk function, thereby providing a hands-free intuitive experience to a large segment of users with lower-limb paralysis. PURE also has the ability to be controlled with a joystick or by another person pushing or pulling the device.

Shared control vision-guided perception system: The vision-guided perception system integrates two RGB-D cameras, two Time-of-Flight (ToF) sensors, and two single-beam LiDAR sensors that are hosted by a Single Board Computer (SBC) [16]. These sensors allow for a near 360° obstacle detection capability effectively up to 7 m. The SBC is connected to a speaker, providing an audio interface and issuing alarms when the chair approaches obstacles. Much like driver assistance control in motor vehicles, PURE's shared control system is used to improve driving experience and reduce rider attentional demand. The perception system is combined with a custom a Passive Artificial Potential Field (PAPF) approach to allow for real-time shared control between the rider and device. Specifically, the shared control system provides intuitive navigation with deceleration assistance, obstacle avoidance, and haptic/audio feedback to effectively mitigate collision risks.

USABILITY ASSESSMENTS

Various assessments to test the usability of PURE (i.e., braking, balance, safety, maneuverability, driver assistance) were conducted with mWCUs and able-bodied users (ABU). The mWCUs had various levels of torso mobility due to SCI or other neurological impairment. Institutional Review Board approvals were obtained along with all participants providing informed consent.

To assess the TES, 20 young adult participants (10 mWCUs (5f, 26.0 ± 5.3 yrs) and 10 ABU(5f, 24.6 ± 3.2 yrs)) rode the device through obstacle courses replicating realistic indoor environments following the US building codes [15]. The course consisted of taped outlines representing a bathroom stall, static obstacles, moving obstacles at three speeds, and straights, slides, and turns with four width boundaries ranging from 61 – 244 cm. The course was repeated once per width and per control mode (hands-free or joystick). Four attributes of performance were examined: effectiveness (i.e., number of collisions), efficiency (i.e., successful completion time), comfort (NASA TLX scores), and robustness (i.e., index of performance). Repeated measures MANOVA tests found that the effectiveness, efficiency, robustness, and comfort (all NASA TLX scores, except physical demand which was higher for hands-free control $p < 0.001$) were similar for hands-free and joystick control and between mWCUs and ABUs for all sections ($p > 0.05$). These results suggest that the TES provides an effective method for controlling this new omnidirectional wheelchair by only using motions of the torso (including small movements).

To assess the shared control driver assistance system, 20 young adult participants (10 mWCUs (6f, 27.4 ± 1.6 yrs) and 10 ABU (5f, 23.6 ± 1.1 yrs)) rode the device through two test courses (S-Turn and Zigzag) [16]. The S-Turn course widths were 70 cm or 80 cm, while the Zigzag course had fixed 90 cm paths with 65 cm or 70 cm narrowing sections. Each participant completed 24 trials in total (2 test courses × 2 control schemes (with or without shared control assistance) × 2 widths × 3 trials per condition). A Collision Index was calculated and defined by assigning weights to different types of collisions, namely “touch” (x1), “move” (x3), and “failure” (x9). These weights reflect the severity of the collision and the potential risk of structural damage. Efficiency (completion time), comfort (NASA TLX scores), and three measures of effectiveness (number of touch collisions, move collisions, and failures) were also examined. Repeated measures MANOVA tests found the performance metrics, excluding average failures due to rarity, were significantly influenced by test course configurations ($p < 0.001$), shared-control utilization ($p < 0.001$), and their interaction ($p = 0.005$), with no notable differences between user groups ($p > 0.05$). A post-study questionnaire aimed to gather insights into participants’ preferences regarding the shared-control design. Using a 4-point scale, participants consistently found the shared control assistance to be intuitive (average score: 3.55), natural (3.15), and safe (3.5). These results suggest that shared control significantly reduced collisions and cognitive load without affecting travel speed, offering intuitive and safe operation.

DISCUSSION

Through the lens of WCUs, we developed PURE, the first-of-its-kind hands-free ballbot wheelchair. PURE is an intuitive, compact, self-balancing, ball-driven mobility device for people with lower-limb disability. It offers elegant, hands-free organic movement controlled with upper-body movements.

Future work is exploring further improvements. Our next generation prototype is seeking to support riders up to 104 kg (~80th percentile male weight) and operate at a maximum speed of 2.7 m/s (~average human jogging speed) while still maintaining its compact footprint. We are addressing maintaining stability in uneven terrain and loss of power. We are also exploring the use of autonomous and semi-autonomous navigation to allow for way finding, crowd navigation, and self-docking. A unique feature of PURE is hardware modularity. It will have quick (dis)connect features to allow for compact and lightweight modules (ideally less than 9 kg each). The future vision is to make PURE easily transportable in a vehicle or airplane (stored as carry-on luggage), allowing users full independence with respect to the vehicles that they use.

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