Embodied-AI Wheelchair Framework with Hands-free Interface and Manipulation

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Abstract—**Assistive robots can be found in hospitals and rehabilitation clinics, where they help patients maintain a positive disposition. Our proposed robotic mobility solution combines state of the art hardware and software to provide a safer, more independent, and more productive lifestyle for people with some of the most severe disabilities. All-terrain tracks, a retractable roof, two manipulator arms, and a hard backpack are the most obvious hardware additions to the standard power wheelchair platform. There are a number of sensors that collect environmental data and processors that generate 3D maps for a hands-free human-machine interface. The new system can receive input from the user via head tracking or voice command and display information through augmented reality projection into the user's display. The software algorithm uses a novel cycle of self-learning artificial intelligence that achieves autonomous navigation while avoiding collisions with stationary and dynamic objects. The prototype will be assembled and tested over the next three years and a publicly available version could be ready two years thereafter.**

Keywords: Embodied Intelligence, Robotic Wheelchair, Human Machine Interface, Assistive Navigation

I. INTRODUCTION

Smart (robotic) wheelchairs have in recent decades become the subject of international research and development. Multiple groups are developing prototypes to test the latest input method, or implement a challenging operating mode algorithm. See [1] for a review of the smart wheelchair research between 2005 and 2015. See [2] for a description of the intelligent power wheelchair we proposed in 2015. In 2017 researchers from the developing nation of Bangladesh built their SW with windshield wiper motors, and sonar with accelerometer for 2D mapping [3]. Their prototype was able to follow a path that it had previously followed and recorded. In 2018 a group in Sri Lanka developed a SW with a laptop as the main controller [4]. The user could choose voice, gesture, or joystick to provide the input, but they only had five voice/gesture commands: break, left, right, forward, backward. Also in 2018, researchers in Germany developed a SW with a GPS sensor, an absolute position sensor and medical sensors to monitor the user's ECG and blood pressure [5]. By 2019 engineers in Lebanon had put together a fully autonomous SW using infrared computer vision [6]. That same year a second team in Sri Lanka came out with a SW autonomous navigation as well as health monitoring sensors [7]. In 2020 a team of scientists in India made a SW that would autonomously follow a guide [8]. That same year collaborators from Saudi Arabia, New York and California developed a vision based SW for hands-free mobility [9]. In 2021 a team from Romania used fuzzy control of the robotic arm for a smart electric wheelchair to assist people with movement disabilities [10]. A team in Japan developed a power wheelchair for the physically weak, who can still use their feet to control an accelerator and break petal [11]. Spanish researchers are working on virtual reality simulations of robotic wheelchair tasks [12], and teams in Saudi Arabia and Bangladesh continued making strides towards the ultimate hands-free interface, namely brain control [13]. The most complete autonomous robotic wheelchair prototype of 2021 came from scientists in Korea [14].

Ever since the onset of the COVID-19 viral pandemic in early 2020, and continuing through the writing of this paper, the majority of potential robotic wheelchair users have come under threat of serious illness and even death. It is therefore more important than ever that we develop embodied artificial intelligence (AI) [15] tools to keep the elderly out of nursing homes, and reducing the load on in-home caregivers.

We designed a hands-free human machine interface (HMI) for power wheelchair users, but the same concepts apply to more general users. The HMI research focuses on hands-free user input to the machine, hands-free user output for automated navigation, and hands-free user output for manipulation. The non-HMI research includes stability and comfortability modeling, 3D mapping, and autonomous interaction with the surroundings. Following this introduction, is a description of our RW's hardware and software constituents in Section II. In Section III we add details about the testing of the various systems, followed by concluding remarks in Section IV.

II. CONSTITUENTS

As shown in Figure 1 the proposed Robotic Wheelchair (RW) consists of several hardware systems recognizable from other applications. Most notable are perhaps the all-terrain tracks, the manipulator arms, and the retractable roof. Less visible are the power distribution system and the suite of environmental sensors. The data from the sensors is used

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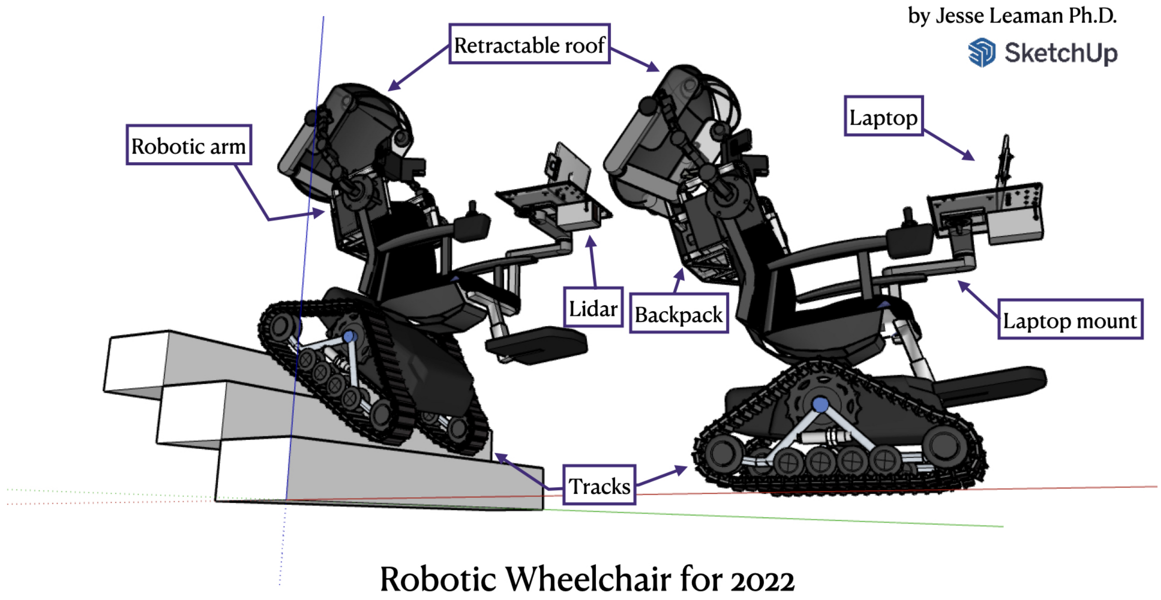

Fig. 1. Artistic rendering of the proposed Robotic Wheelchair. It is designed by a scientist with quadriplegia to be an all-weather all-terrain independent living vehicle. It has a hands-free interface and several operating modes intended to increase the user's safety and productivity.

by the onboard computer to generate a sophisticated human machine software interface with several operating modes.

A. Hardware

All hardware systems are designed to attach to most power wheelchairs, and can be fairly easily removed for maintenance or travel. All are modular and upgradable so individual systems can be swapped for the latest version without having to remake the entire RW. Figure 1 shows a 3D sketch of the RW in the middle of navigating stairs (left) and raising a retractable roof (right). Table I lists all of the hardware components included in our proposed RW.

1) Platform: The platform consists of the seat, the main batteries, and the wheelbase. The power for propulsion is provided by two 12 V Li-ion rechargeable batteries. The seat can tilt or recline to reduce the chance of pressure sores, and the footrests extend like a recliner to maintain flexibility. This version of RW has tracks instead of wheels. They are modeled after ATV tracks with a size 75% of the off the shelf kit. The tracks are made of mostly carbon fiber and aluminum to keep the mass down, with treads made of recycled car tires. They enable the RW to travel up and down stairs, traverse uneven terrain, all the while being safe to use indoors on hardwood or carpet.

2) Backpack: The 3 feet tall backpack is made of aluminum and is bolted to the back of the 2 feet wide seat. Inside it carries a smaller 12 V Li-ion rechargeable battery, the controller for the LED light system, and a small storage space. Along the outside are light strips, and attachment points for the robotic arms and the retractable roof.

3) Human-Machine Interface: The basic human machine interface (HMI) is a laptop computer attached to the platform via a mount-n-mover with laptop tray. The laptop has a head tracking mouse, and the user can click select by dwelling on a location on the screen. The more sophisticated HMI is a glasses configuration with augmented reality, eye tracking, and gaze recognition. The latter may be too confusing for some users to utilize comfortably. A secondary source of input can be voice recognition, but the accuracy diminishes greatly in noisy environments. However under the right conditions and with the best recording equipment, language can be significantly more efficient than the single clicks of gaze control. The optimal HMI therefore includes a hybrid input system, where the user can decide which method to use for a given task and environment.

4) Robotic Arms: Given that the intended RW operator cannot use their arms, a set of two robotic arms can perform many needed tasks. Positioned near the user's shoulders and having a length similar to an adult arm, these devices can improve productivity and independence. Each unit has 9 degrees of freedom and can perform tasks like pressing buttons. Together the pair can work on more complicated tasks like using utensils to cut food or moving items from one location to another.

5) Retractable Roof: The retractable roof (RR) is inspired by cabriolets that give some lucky automobile owners the ability to drive with the top down whenever the weather permits. Aside from the obvious size difference, the RR is mostly carbon fiber with some aluminum brackets, so it is relatively light weight and folds up to be very compact. It is raised and lowered using the robotic arms, and can protect the user from rain or too much sun.

TABLE I
ROBOTIC WHEELCHAIR HARDWARE LIST.

Name	Cost ($)	Source
Power Wheelchair	15000	Permobil
Laptop Mount	1300	Mount-n-Mover
Computer	1300	Macbook Air
LED Lights w/ Controller	160	Xkglow
iPhone w/ Mount	1450	Apple
Lidar	1000	DJI Livox Horizon
Backpack	500	In House
Rechargeable Battery	200	Amazon
Inverter	80	Amazon
Robotic Arms	10000	In House
Retractable Roof	4000	In House
All-terrain Tracks	4000	In House
AR Glasses	1000	Google
Total	39990	

B. *Software*

Some operating modes have variables that have to be configured once in a while, but since they run in the background they could be considered non-HMI. For security the RW must function only if an authorized user is attempting to use it, and precautions have to be made to prohibit remote operation. We will implement at least four levels of security. As shown in Table II the operating system has three levels (standard, silver, gold), the first are included with the RW, and the other two are for the more advanced user who may also be surviving with the most severe disability. Figure 3 shows the standard autonomous navigation system. Not shown are the standard operating modes: automatic communication, automatic leveling, and emergency signaling. They run in the background independent of navigation. The four step cycle, or Quad-cycle Neural Network (QCNN), runs continuously until the user arrives at their destination. Then the silver or gold modes are engaged to park, follow a guide, climb stairs, or activate the robotic arms. The QCNN model maintains user safety, while minimizing travel time to reach a destination, and maximizing the quality and improvements of the 3D map after each journey.

TABLE II
ROBOTIC WHEELCHAIR HMI SOFTWARE LIST.

Name	Code	AR*	Level
Automatic Communication	AC	No	Standard
Automatic Leveling	AL	No	Standard
Emergency Signaling	ES	No	Standard
Collision Avoidance	CA	Yes	Standard
3D Mapping	3M	No	Standard
Gesture Recognition	GR	No	Standard
Path Planning	PP	Yes	Standard
Guide Following	GF	Yes	Silver
Docking	DK	Yes	Silver
Robotic Arm Asst.	RAA	Yes	Gold
Stair Climbing	SC	Yes	Gold
*Interactive in real-time			

1) Automatic Communication: The AC mode runs behind all other modes and has to be configured to the user's specifications in each. Automatic communication can take place between autonomously navigating PWs and pedestrians, as well as between PWs. The first type of communication is via LEDs, where changes in heading are announced with blinking yellow lights on the side of the machine to which it's heading. Another light signal is flashing blue and red lights during emergencies. Then there is communication between machines when they are traveling together following a guide, signaling each other via bluetooth. Lastly there is communication between large vehicles like buses or trains and the PW using DK mode to park within.

2) Automatic Leveling: Each user will have a preferred seat tilt angle, reclined enough to be comfortable, but not so much that he or she is not in a position to drive. Based on accelerometer data, the seat will change the reclining angle to maintain the same relative tilt no matter what the gradient of the terrain happens to be. The default seat tilt is set to be 10 degrees passed vertical since the maximum safe gradient is 10 degrees. If the RW travels up a 10 degree incline the seat will tilt up to vertical, but if the RW travels down the same incline the seat tilts back to 20 degrees passed vertical. Once the user sets their favorite reclining angle, the AL mode runs in the background.

3) Emergency Signaling: The ES mode leverages stability modeling and sensory information to determine whether the user is experiencing an emergency or not. This mode can run in the background behind all other modes and it can be configured to the particular user's tolerance. Sensors include an inertial measurement unit (IMU) for PW orientation and a suite of biometric monitors tracking the user's health condition. These bluetooth connected devices provide the wearer's temperature, heartbeat, and blood oxygenation. If any measurements are outside the user's "normal" levels, like if the PW is laying on its side, or the user has a temperature above 101^{o}F, an emergency is declared and a message is sent to their contact list.

4) Collision Avoidance: Similar to the 3M mode, the CA mode runs in the background of all other modes except ES. The user is given the opportunity to configure the CA mode to match their tolerance for speed and need for a large buffer. If the buffer is set too high, the machine may not be able to pass through narrow doorways. If the buffer is small the machine could pass through gaps more quickly, but that could make the user uncomfortable.

5) 3D Mapping: The 3M mode is both power and memory intensive, so the user has the option to reduce the point cloud by selecting a lower frame rate. Map rendering can be requested at any time, but is not done automatically so that processing power is conserved. 3M is vital for the CA and GR background modes, as well as GF, DK, and PP interactive modes. The 3M for a RW is not very different from the 3D mapping system in an autonomous automobile finding a parking space in a parking garage [16].

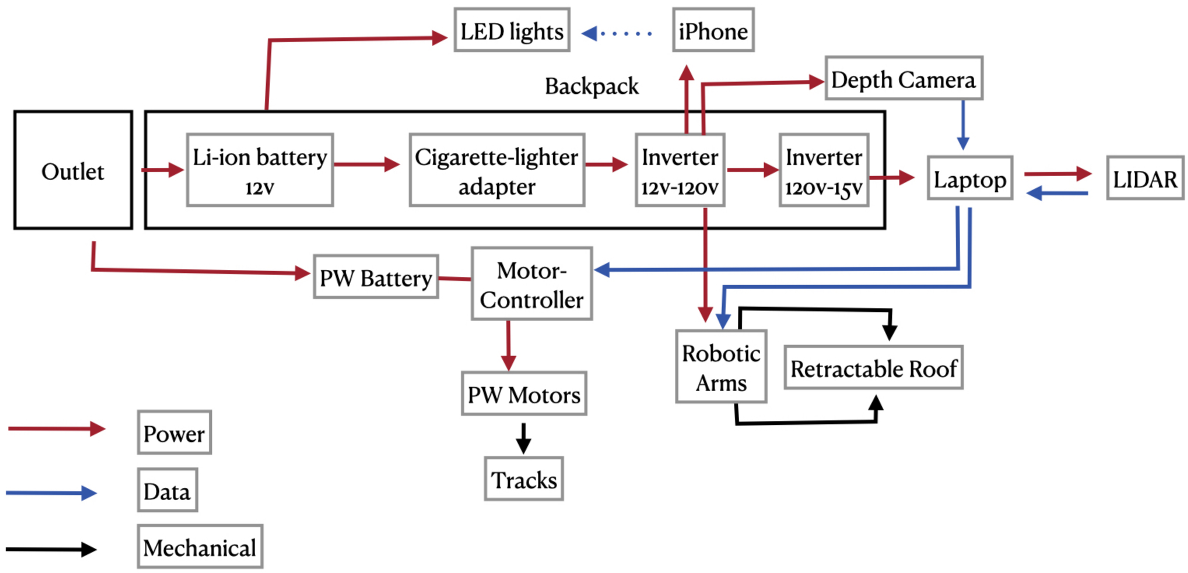

Fig. 2. Chart of the proposed Robotic Wheelchair's hardware and the path of the power and data flow. It has a hands-free interface and several additional parts not available on a standard power wheelchair.

6) Path Planning: In PP-mode a 3D map is projected until the user selects a destination. The user is then prompted to choose between exploring-based automated navigation (EAN), and object-based automated navigation (OAN). When the EAN mode is used the heading is selected with a compass, and GPS, while detecting and avoiding obstacles on the way. During EAN a 3D map and database of obstacles detected is produced. In OAN the algorithm determines the quickest route from the 3D map and uses objects on the way to stay on course. During each trip the map becomes more accurate and detailed, while keeping a log of all objects encountered. This data can be used to distinguish between permanent structures like walls and doors, or transient objects that periodically show up. For example there might be a garbage can on the sidewalk every Thursday, or a "wet floor" sign in the hallway every evening when the janitor mops up.

7) Gesture Recognition: The GR mode is used in the background of the GF and PP modes, but it serves a different purpose in each. Within the GF mode GR is used to identify potential human guides, distinguishing between people who are just passing by, and a person making eye contact and waving hello. In PP mode GR is used to understand or learn about the PW's environment. A human walking or running towards an intersection with the PW's predicted trajectory could be an obstacle requiring a course correction. If the human makes eye contact and waves hello, we can assume that he or she will adjust their trajectory and the PW can maintain its heading.

8) Guide Following: In GF-mode red rectangles will surround potential guides until the user selects one. Then a green rectangle surrounds and tracks the guide. The GF algorithm will adjust the PW's trajectory to maintain the green rectangle in the center of the field of view, but if the guide moves too erratically the box turns yellow. If the guide is lost the PW stops and red rectangles appear again.

9) Docking: In DK-mode the user is presented with safe parking options. In AR the PW's footprint is displayed as a green rectangle on the ground at the location of a suggested parking spot. After the user makes a selection, the rectangle turns yellow until the PW is squarely inside the box at which time the rectangle turns red. Another scenario involves the RW being picked up by a para-transit bus, where the union of personal vehicle and larger transport vehicle is a multistep process.

10) Robotic Arm Assistant: The 3D map and object database are vital for hands-free user output for manipulation. With one or two robotic arms and an operating mode called the robotic arm assistant (RAA), the user can interact with their environment. In RAA mode the AR projection has rectangles surrounding all objects that have been identified and deemed manipulable. Yellow boxes surround objects currently in range, while red rectangles surround objects that are out of range but could be manipulated if the PW moved closer. Once the user selects an object the rectangle turns green and users are given options of what to do with the object. The manipulator can press or tap on buttons, grab and hold something for a closer look, or retrieve and place objects in the backpack.

11) Stair Climbing: The SC mode has to be activated by the user and has multiple steps for confirmation to give the user the opportunity to change their mind and find a safer route. First CA has to be turned off and then the AL has

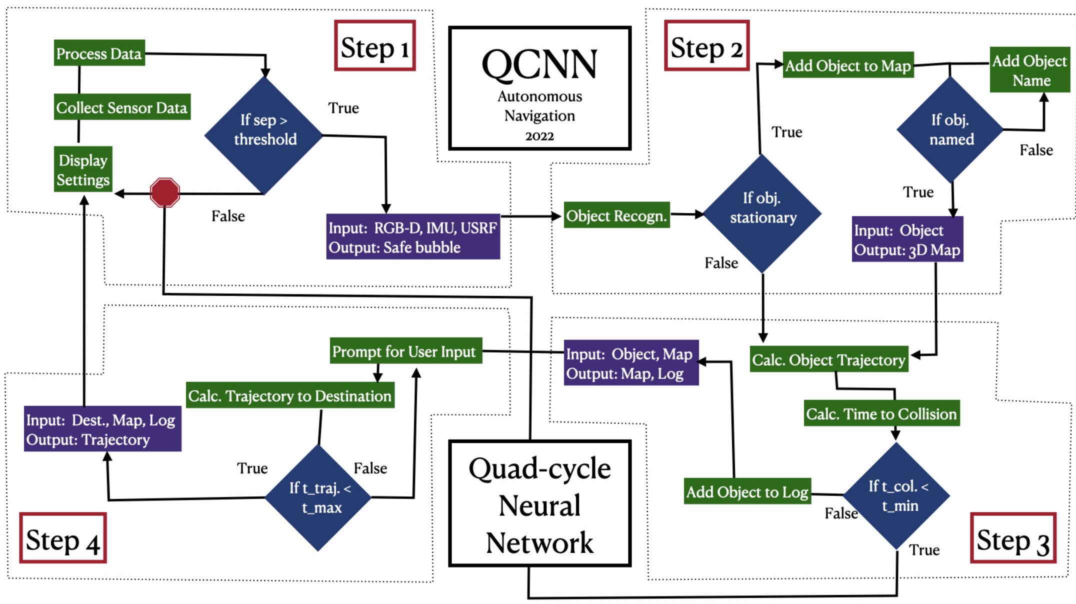

Fig. 3. Chart of the proposed Robotic Wheelchair's software algorithm for autonomous navigation. Step 1 is collision avoidance, Step 2 is the 3D mapper, Step 3 is gesture recognition and trajectory calculator, and the final step is path planning. These four modes continue to cycle until the destination is reached, in a process that minimizes 'thinking time' without sacrificing safety and the ability to build a more accurate map during every trip.

to be suspended. If the user still chooses to proceed, the RW scans the obstacle carefully, in order to determine the appropriate seat tilting angle. Traveling down stairs could be more dangerous than going up, because of momentum and the fact that the tracks could loose their grip. In order to go up a set of stairs, the RW will have to turn around and reverse.

III. Testing

The RW is intended to serve the most vulnerable people in the world, so we must be sure the technology has been thoroughly tested and found to be safe under all conceivable circumstances. First we will focus our simulations on activities that could cause serious injury, including scenarios where the PW tips over or back, or user health emergencies.

Unfortunately, most software is not accessible unless it has been designed to be so from the very beginning using participatory methods [17]. Human trials for this iteration of the RW have been underway since the Fall 2021 semester in when co-author 1 made himself available for participatory design of assistive technology by undergraduate students in an accessible computing class taught by co-author 3. That question and answer process helped determine the utility of certain features and the need for improvements.

Despite the fact that none of the student projects had the functionality to be included as an operating mode, the process revealed that a tutorial guide will be vital to show first time users, including trial participants, how to setup the sensors, turn features on and off, change user preferences, and select items. Quantitatively we will measure the time it took trial participants to accomplish these tasks and the accuracy with which they were completed. Qualitatively we will conduct interviews with the participants in order to determine their level of comfort and confidence in the technology at various stages of the trial. The results from each round of trials will lead to an improved iteration of the HMI and the RW in general.

A. HMI

As discussed in Section II-A3 the ideal Human-Machine Interface (HMI) also known as a Human-Computer Interface (HCI) has a hybrid input system, depending on the user's capabilities and the environment of the RW. Since the focus of this research is a hands-free system, we do not include joysticks or touchscreens as input options. Nor do we consider brain control, because commercially available brain-wave or Electroencephalogram (EEG) readers are currently not accurate enough to distinguish more than a handful of commands. Perfecting the hands-free user input is fundamental to the rest of our research. It has to be accurate, fast, adaptable, and help optimize the user's cognitive load. Common tasks should be easy to learn and intuitive to execute so that they become like second nature after just a few repetitions.

1) Voice Recognition: The first reliable hands-free input method was voice recognition, which has been commercially available for around 26 years, becoming more accurate with every iteration. Nevertheless voice recognition had one major flaw, it lost accuracy in noisy environments. One can improve the accuracy with better microphones and placement closer to the user's mouth, but in extreme situations like a crowded bar or sporting event, that will not help.

2) HTM: In 2011 the head tracking mouse (HTM) became a relatively affordable alternative to voice recognition, and made users more efficient as soon as it was adopted. Interviewer: "how did the HTM change your life?" Subject: "I felt totally liberated, because I could finally use a few applications that I could never really use before. First and foremost was 3D computer aided design (CAD), which gave me the ability to communicate my ideas for technology solutions. Two other programs that required finessed mouse movements were GarageBand and iMovie. I was finally able to maximize my creativity the instant my mouse went wherever I looked."

3) Eyeball Tracking: Most recently, eyeball tracking on glasses has become available with augmented reality display. Brand new users may however be disoriented by such a display so users will need practice, and some less technically inclined trial participants will not even try. Dragging and dropping items in the augmented reality is particularly challenging. Users have to develop exquisite eye control and blink discipline.

IV. Conclusion

The RW is the culmination of 26 years of research to help people with severe disabilities lead safer, more independent, and productive lives. The target user for this embodied AI is a person who is either paralyzed from the shoulders down or no longer has the strength and dexterity to use a joystick to control their PW. In general the same concepts apply to professionals who use both hands in a dynamic, high stress situation, like firefighters battling a blaze or astronauts repairing the space station. For such individuals it would be much more efficient to provide an input to the machine by tracking eye/head movement and dwelling/gaze recognition.

The new RW will have all-terrain tracks made of aluminum, carbon fiber, and recycled car tires. They let the user navigate stairs, indoors or outside, without scratching or otherwise damaging the floor. The RW will also have a retractable roof for all-weather protection, and at least one robotic arm for pressing buttons. Besides the new mechanical systems, the RW has a sophisticated hands-free human-machine software interface, with multiple operating modes. Some of the applications like collision avoidance are standard and are always running in the background to maintain the user's safety. Other applications are available as silver or gold level upgrades. Modes like the robotic arm assistant and stair climber will be interactive via augmented reality display, reserved for only the neediest users, determined to take advantage of any help they can get.

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