Design and Development of Two Generations of Semi-Autonomous Social Telepresence Robots

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***Abstract*—Our research focuses on how a telepresence robot operator, the people with the robot, and the robot itself collaborate so that the operator reaches his/her intended destination. Our research requires higher levels of autonomous navigation so that the robot can, for example, go to a specified destination and follow a person. However, commercial telepresence robots are primarily teleoperated, and only a few provide assisted navigation around obstacles. We present the evolution of our overall design for augmenting two VGo Communications' VGo robots, Hugo and Margo. We detail the requirements and design constraints encountered while developing our telepresence robot platforms.**

I. Introduction

Contemporary, commercial telepresence robots are focused on the concept of telecommunication and remote presence with independent mobility. They are designed for the masses – laypeople, including corporate executives, engineers, sales associates, doctors, caregivers, and students – as opposed to trained robot specialists or roboticists [1]. Most commercial telepresence robot interfaces are designed for teleoperation from a computer; for example, a robot will move forward when the up arrow key is pressed and stop when the key is released.

While the concept seems simple, teleoperating a telepresence robot at this level can be a cognitively taxing task because the user is remote from the robot. First, the user interfaces typically display the robot's live video feed as the dominant feature, which is a "soda straw" view [2] of an unfamiliar environment. Second, due to the mobility afforded by telepresence robots, the information, including the robot's video, must be transferred wirelessly, and the connection quality depends the available bandwidth, latency, and packet loss [3]. These issues are not unique to telepresence robots, yet only a few commercial telepresence robots currently provide assisted navigation around obstacles (e.g., Anybots' QB) or to local destinations selected in the robot's view (e.g., Gostai's Jazz). InTouch Health and iRobot's RP-VITA can autonomously navigate to a selected destination, which was recently approved by the FDA [4]. Research telepresence robots implement a number of navigation behaviors with varying levels of autonomy, including collision avoidance (e.g., [5]–[9]), selecting a local destination or trajectory (e.g., [6], [8]–[10]), follow a person (e.g., [5]), and go to destination (e.g., [5], [6], [9], [10]).

MIT Technology Review's Tom Simonite noted the difficulty he experienced during a test drive [11]: "In a group conversation, I would clumsily spin around attempting to take in the voices and body language outside my narrow range of vision. When I walked alongside people, I sometimes blundered into furniture, or neglected to turn when they did." These mistakes may be seen as a reflection of the telepresence robot operator [11]. Our research investigates how people with cognitive and motor impairments can operate telepresence robots in remote environments in a safe and socially acceptable manner, which will require autonomous and semi-autonomous navigation behaviors. Our primary goal was to incorporate additional sensing and processing capabilities to support the "go to destination" and "follow person" navigation behaviors.

Fig. 1. Margo (left robot) showing the front view of our v1 design with Hawaiian shirt and tricolor LEDs. Back panel is shown on a sibling v1 robot, Largo (right). Hugo (center), v0 prototype, features a blue LED necktie.

Since the premise behind a telepresence robot is that it serves as a physical representation of the remote operator, its appearance is equally as important as the functional and technological requirements [1]. Research in human-robot interaction (HRI) has shown that a robot's physical appearance, structure, and form establish the social expectations of it [12]. It has been shown that human-like robots are preferred for social roles [13]. Further, robots with mechanical appearances are viewed as aggressive and angry [13], and an overly sophisticated appearance may lead to underwhelming interactions [14]. Schaefer et al. [15] showed that a robot's physical form influences its perceived trustworthiness, which could have severe implications, for example, when a remote

TABLE I
KEY FEATURE SUMMARY OF VGO COMMUNICATIONS' VGO ROBOT

Unit cost	$6K plus $1,200 annual service contract
Drive	2 wheels and 2 trailing casters
Wheel size	7 in (17.8 cm) diameter
Wheel base	12 in (30.5 cm)
Top speed	2.75 mph
Height	48 in (121.9 cm) fixed
Weight	• 18 lbs (8.2 kg) with 6 hour battery • 22 lbs (10.0 kg) with a 12 hour battery
Battery type	Sealed lead acid battery, 12V
Auto charge	Auto-dock within 10 feet (3.0 m) of docking station
Microphones	4 around video screen (1 front/back pair on each side)
Speakers	2 (woofer in base, tweeter in head below the screen)
Screen size	6 in (15.2 cm) diagonal
Number of cameras	1 forward facing webcam with 2.4 mega-pixels, located above the screen
Camera pan-tilt	No independent pan. Yes, 180 degree tilt
Connection type	• WiFi (802.11b/g 2.4GHz, 802.11a 5.0GHz) • 4G LTE (requires separate contract and sim card)
Bandwidth	200kbps up to 850kbps (up and down); recommended 1.5Mb (up and down)
Operating systems	• Windows 7/Vista/XP with SP3 • MacOS 10.6.x or higher (in beta)
Navigation control	• Mouse "Click and Go" widget • Arrows keys with customizable acceleration profile • Proportional joystick widget (in beta)

worker engages with teammates via telepresence robot. Thus, it was imperative that we accomplish our primary goal in an aesthetically pleasing manner. In this paper, we present the evolution of our overall design for augmenting our two VGo Communications' VGo robots, Hugo and Margo (Fig. 1).

II. VGO COMMUNICATION'S VGO ROBOT PLATFORM

We selected the VGo Communications' VGo robot as the base for our system as it has a sophisticated audio and video communication system.[1] VGo App is VGo Communications' video conferencing software. It supports both robot calls (i.e., from a laptop/desktop computer to a robot) and also desktop calls (i.e. between two laptop or desktop computers). The user interface is primarily a view of the robot's live camera stream with a small video of the user in the top right.

The specifications of the standard VGo robot are listed in Table I. Additionally, the VGo's base has a front bumper and four infrared (IR) distance sensors. There is one IR distance sensor centered in front, and one on either side of the front (on the left and right); these are primarily used to warn the user about obstacle detection. The fourth IR distance sensor is located in the rear and assists with docking on the charging station.

The overall appearance of the VGo robot is pleasing. The landscape-oriented screen is encompassed by a ring of black plastic and thus resembles a head [20]. The tweeter speaker makes the robot operator's voice appear to come from the head as a local would expect. Its height is that of a small person (48 in), which Lee et al. [21] note to be on the slightly small side of "just right." VGo's body has a slight curve and is covered completely with a white, lightweight plastic [20]. Its iconic appearance resembles Eve from the Disney/Pixar film *WALL-E*, yet remains gender-neutral [12], [22].

[1]Synthesized from [16]–[19] and our own robot use.

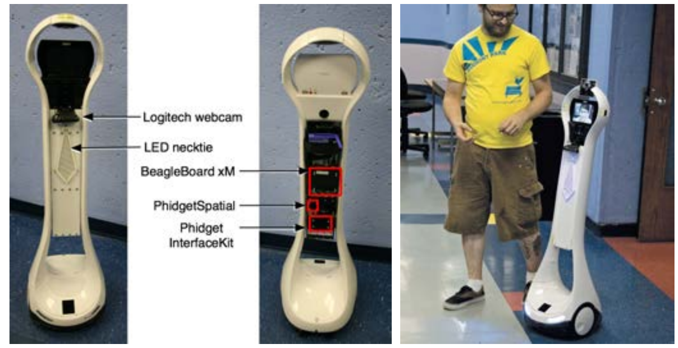

Fig. 2. Front and back views of our augmented VGo robot, Hugo (v0).

III. AUGMENTATION OF A STANDARD VGO: HUGO (V0)

A. Selected Components

We augmented Hugo with additional processing and sensors. We selected a BeagleBoard xM-B [23] with an ARM Cortex-A8 1GHz processor with 512 MB RAM, which ran Ubuntu 10.10. The Beagleboard measured 3.25 in×3.25 in, and required 5V. It had a DVI port, a RS-232 serial port, an ethernet jack, stereo input and output jacks, and a USB hub.

We added a second USB hub, and connected five USB devices: a wifi card (Linksys wusb54g ver 4), two Phidget devices, a webcam, and an IR transceiver. The PhidgetSpatial 3/3/3 board had a three axis compass, gyroscope, and accelerometer. The Phidget 1018 InterfaceKit (IFK) had 8 analog input ports, 8 digital input ports, and 8 digital output ports. The Phidget IFK illuminated four blue status LEDs to indicate when the robot's internals (i.e., BeagleBoard) were powered on, as per [24]. Magnetic sensors located in the bottom of the robot were connected to two digital input ports, and custom magnetic encoders on each of the robot's wheel hubs measured odometery.

The BeagleBoard received latched robot movement commands over TCP from a custom webUI (see [25]). A user could issue multiple of the same low-level movement commands (i.e., forward, backward, turn left, turn right). An IguanaWorks IR transceiver emulated the VGo remote control, and sent the robot movement commands to the VGo base using the Linux Infrared Remote Control (LIRC) package [26].

The standard VGo robot has one camera above its screen, which can be tilted down for navigation assistance. Given its limited field of view, we found that it is not possible to simultaneously use the camera for conversation and navigation [3], [16]. A Logitech WebCam Pro 9000 streamed a downward facing view of the base of the robot using gStreamer over UDP.

B. Resulting Design

To people physically present with the robot, it appears to only have one function – mobile video conferencing. It was important to mount the additional sensing and computation in a hidden manner to maintain the VGo robot's aesthetic design. We mounted all of the sensing and computation components on two custom acrylic panels within the vertical space between the two stocks (23.6 in×4.1 in×3.4 in) below the robot's screen. We used 0.25 inch depth acrylic for rigidity. We chose white for Hugo's front panel to match the standard VGo's dominant color, and the back panel was a dark, translucent bronze to minimize attention. We placed the downward facing webcam between the acrylic panels and the robot's screen.

Since human-like robots are preferred for social roles [13], we customized Hugo's "shirt." We designed a tie to house the four blue status LEDs, which illuminated an etched striped pattern (Fig. 2); although a tie has been traditionally associated as masculine, there are a number of variants (e.g., necktie, bow tie, cross-over tie, bolo tie, cravat, ascot, scarf) worn as part of a uniform or as a fashion statement. The long necktie style was chosen because of its familiar shape and its ease of status visibility from its large size (i.e., length and width).

C. Discussion

We discovered several technical shortcomings with our v0 prototype. First, providing robot movement commands by emulating the VGo remote control yielded slow and jerky motions, in comparison to fast and smooth motions achieved when driving the robot with the VGo App. Emulating the remote control also did not allow for simultaneous translation and rotation. Second, our custom encoders did not have sufficient resolution to make small adjustments, such as turning 10 degrees left. Finally, the BeagleBoard did not have sufficient processing for streaming the down facing webcam, processing sensor information, and receiving robot movement commands, and we had not yet begun to address the semi-autonomous navigation behaviors. We formalized our requirements when developing our second prototype, Margo (v1).

IV. Requirements and Design Constraints

First and foremost, we must retain the use of all or most of VGo Communications' existing features. In particular, we must utilize the robot's bidirectional audio and video communication system (both hardware and software) (Requirement 1; R1). We must also utilize the robot's existing power resources and integrate into the charging system without disruption to the standard VGo system (R2). That is, we must power the robot and all of our additional components using the 12V lead acid battery or 19V wall or dock chargers (Constraint 1; C1).

The augmented robot's run time must be at least 2 hours (R3). Assuming a 2 hour run time with the large capacity 15Ah battery (C1), the additional components combined must draw less than 54W per hour (C2), as the standard VGo robot draws 3A (36W) per hour at peak. All additional components must be commercial off-the-shelf (COTS) components and well supported by the robotics community (R4). The selected components must either be well supported under ROS [27] or have their own software APIs for programming purposes.

We must retain the robot's friendly appearance (R4). We must fit the additional components within the VGo's footprint (C3) in a manner that maintains its streamlined industrial design (C4).

In order to investigate autonomous and semi-autonomous navigation behaviors, the robot must be able to map an unknown environment (R5) and perform basic localization (R6). We chose to incorporate a laser range finder and an inertial measurement unit (IMU) [28]. The laser must be mounted low to the ground for mapping purposes (C5) within the VGo's footprint (C3), and the IMU must be mounted in the center of the robot's angular rotation axis and also parallel to the Earth (C6) in a streamlined manner like the rest of the VGo robot (C4).

We also needed advanced sensing for interaction with people present with the robot who may be asked to provide navigation assistance (R7). We chose to incorporate a Microsoft Kinect to provide a dedicated forward facing, color camera and 3D information from an IR painter/camera pair. The Kinect must be mounted at an appropriate height in order to capture useful and interesting data from these interactions. The Kinect must be mounted at the highest position possible on the VGo robot (C7) – atop its existing camera.

We needed the robot to have a dedicated camera for driving (R8). The downward facing webcam must also be mounted at the highest position possible (C7), thereby allowing the widest field of view of the area surrounding robot's base for navigation purposes. Both the Kinect and downward facing webcam must be mounted atop the VGo in a manner that maintains the robot's industrial design (C4).

V. Margo (v1)

A. Selected Components

We augmented the standard VGo using largely COTS components. The BeagleBoard was replaced with a fitPC-2 [29], running Ubuntu 12.04 LTS and ROS fuerte. The fitPC-2 has an Intel Atom Z550 2GHz processor with 2GB RAM. It was chosen for its small size (4 in$\times$4.5 in$\times$1.05 in), wide power range (8-15V), and efficient power consumption. It has onboard 802.11b/g WiFi, a DVI port, an ethernet jack, audio input and output jacks, and 6 USB 2.0 ports. A heat sink and cooling fan are used to dissipate residual heat. The fitPC-2 connects to the VGo robot using two USB RS422 adapters.

A Hokuyo UGH-08 laser and a MicroStrain 3DM-GX3-45 inertial measurement unit are used for navigation purposes [28]. An array of six Sharp IR distance sensors provide cursory information about the space behind the robot. A Microsoft Kinect is used for capturing the interactions of people physically present with the robot. A Logitech C910 webcam provides a downward looking view of the area around the robot's base.

Infrastructure was added to connect and power the components, including a 4-port USB 2.0 hub and a Phidget 1019 IFK with built-in 6-port USB 1.1 hub. The Sharp IR distance sensors interface with the Phidget 1019 IFK using the corresponding Phidget 1101 analog adapters. A Minibox DCDC-USB buck-boost power supply regulates the power from the 12V battery to the laser and Kinect. A custom signal and power routing board bridges the wiring between the separate components in the robot's left stock, right stock, three acrylic panels located between the two stocks, the hat containing the Kinect and Logitech webcam, and base laser. Three adjustable step down switching regulators (model DE-SWADJ 3) on this board provide power to the fitPC-2, the cooling fan, the USB 2.0 hub, the Phidget 1019 IFK, and four tri-color LEDs. A second custom power board located in the base channels powers our augmentations from the highest voltage power source.

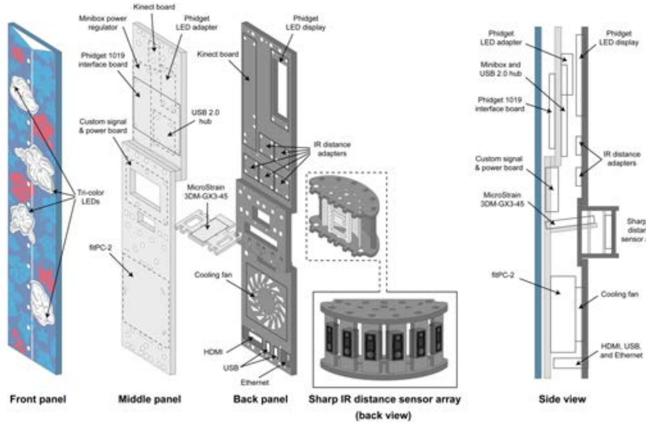

Fig. 3. Expanded and side view of Margo's augmentation panels (v1).

Fig. 4. (Left) The Hokuyo UGH-08 laser is mounted in the forward center of the VGo robot's base over the base speaker. (Right) The laser's formerly orange cap has been covered with white silicon Sugru to visually minimize it.

B. Resulting Design

The majority of these components are mounted on three custom 0.25 inch acrylic panels (Fig. 3). The middle panel first mounts between Margo's stocks, and the front and back panels mount to it. The front panel mount screws blend with a vertical line of decorative screw "buttons." Nuts to mount components on the panels were held captive between two 0.0625 inch layers. Perforations were cut to reduce the weight of the acrylic panels.

Margo features a Hawaiian shirt, which implies a fun, friendly personality [30] and appeals to a large audience [22]. The shirt is bright blue [13] and decorated with tropical flowers. Four flowers are clear with inset RGB LEDs, which are used to indicate state (Fig. 1 left robot). For example, green may indicate that the robot is currently in use, which matches with VGo's "in call" status, or red that the wifi signal connection is weak. The gender-neutral Hawaiian shirt motif is suitable for both male and female operators [21], [22].

The back of the robot is designed for an administrator's use only. The back panel and the IR sensor array are translucent, dark gray acrylic, and the Hawaiian shirt pattern is repeated in white (Fig. 1 right robot). Our goal was to deemphasize the partially exposed components, namely the fitPC-2's cooling fan, the IR sensor array, and the administrator's access to the internal system. We incorporated the Phidget 2×20 character display into the back plane at the top of the shirt to show system and status information (e.g., power levels, wifi strength). Below the IR array, we exposed the fitPC-2's USB, ethernet, and DVI ports and a recessed soft reset button for debugging purposes.

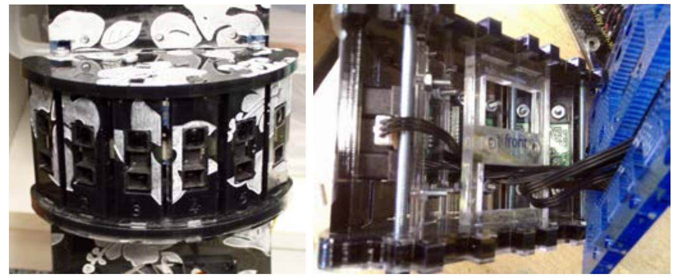

Fig. 5. External (left) and internal (right) views of rear IR array bustle.

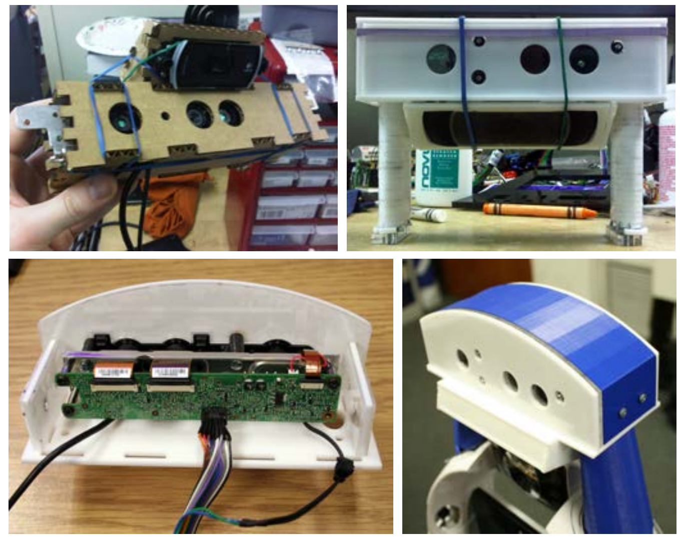

Fig. 6. The "hat" contains a Kinect and down facing Logitech C910 webcam. Initial rectangular prototypes in cardboard (top left) and acrylic (top right). (Bottom left) Internal view of Kinect camera board. (Bottom right) Final rounded version shown mounted above the VGo's tilt camera.

The standard VGo has an upward facing IR distance sensor in the forward center front of the robot's base to detect a tall obstacle (e.g., table). We adjusted the position of the IR sensor in order to recess mount the laser over the base speaker (Fig. 4). Additionally, the laser's formerly orange cap has been covered with white silicon Sugru to minimize it visually. The UGH-08 laser has a 240° field of view; however, the VGo's vertical stocks block the laser's view such that it only returns meaningful values for the front 180°. We designed an array of six Sharp 2Y0A02 IR distance sensors (Fig. 5) to provide cursory information about the space behind the robot within 8 to 60 inches. The IR array bustle extends from the back panel but remains within the form factor of the VGo's base (Fig. 1 right robot).

Finally, the Kinect and Logitech C910 webcam are housed in a "hat" which sits above the VGo's servo tilt camera. We removed the plastic Kinect exterior and separated the three circuit boards. Only the camera board is housed in the hat (Fig. 6 bottom left), and the remaining processing board and motor board are mounted within the shirt (Fig. 3). Functional prototypes were rectangular in shape (Fig. 6 top). However, the rectangular shape detracted from the VGo robot's curved body design, and we increased the height of the hat to incorporate an arch to soften the harsh line (Fig. 6 bottom). The final version of the hat adds approximately 6 inches to the robot's height, increasing its total height to a socially comfortable 54 inches [21].

C. Software

A fitPC-2 running Ubuntu 12.04 LTS and ROS fuerte controls the motors and processes sensor information. The use of ROS is prevalent among academic and industry researchers and, furthermore, is well suited for the complexity of our system. We are able to leverage the distributed architecture and modular communication ROS provides [27]. Fig. 7 provides an overview.

1) Communicating with the VGo Base: The VGo robot uses serial communication to allow the “head” and “base” to exchange information. We modified this connection by inserting a fitPC-2 between them. The fitPC-2 establishes serial communication with the base through a custom ROS node, `vgo_serial_comm`, which has two modes. In the first mode, the node connects the VGo’s head and base together by reading incoming packets and forwarding them to the appropriate destination; we refer to this as the serial passthrough mode.

In the second mode, the fitPC-2 is able to directly communicate with the VGo base using the VGo library.[2] The `vgo_serial_comm` node publishes four topics every 100 ms: `power_data`, `ir_data`, `bumper_data`, and `encoder_data`. The `power_data` topic provides the base’s status with respect to power, such as if the robot is being charged, if the battery is indicating low power, if the base is being reset or shutdown.

The values from the four Sharp IR sensors in the VGo base and the two switch sensors in its front bumper are published to the `ir_data` and `bumper_data` topics, respectively. The VGo robot features high resolution motor encoders. Values of the left and right motors are published on the `encoder_data` topic. We have empirically determined that 5.18 encoder clicks is equal to a 1 degree turn of wheel. The `vgo_serial_comm` node subscribes to the `cmd_vel` topic, and the `x` value of the linear component and the `z` value of the angular component of the `Twist` message are used to set the translation and rotation of the motors.

2) Emulating the VGo IR Remote Control: The VGo remote control activates user interface functions on the robot’s head: answering and hanging up a call, tilting the VGo’s camera up and down, turning the robot’s volume up and down, muting the volume, and taking a picture. From our `lirc_vgo_remote` node, we emulate a button press by executing `irsend` calls at the command line and specifying the corresponding hex code.

3) Utilizing ROS Packages and Stacks: To enable the rapid development of robot specific code for the VGo robot, we have built upon existing ROS stacks and packages contributed by the community. We utilize the `hokuyo_node` package for the UGH-08 laser, the `microstrain_3dmgx2_imu` package for the IMU, the `openni_launch` unary stack for the Kinect, and the `gscam` package for the webcam’s video. These nodes are instantiated as `laser`, `microstrain_3dmgx2_imu_node`, `hat_kinect_camera`, and `hat_down_webcam`, respectively, in Fig. 7. Additionally, we utilize the `gmapping` package for generating maps from the laser and the robot’s encoder values, and the `amcl` package for localizing on a given map with the robot’s location in 2D space and orientation. We utilize the `joy_node` package with a USB gamepad for teleoperation; the node is instantiated as `gamepad`.

[2]Property of VGo Communications; used with permission.

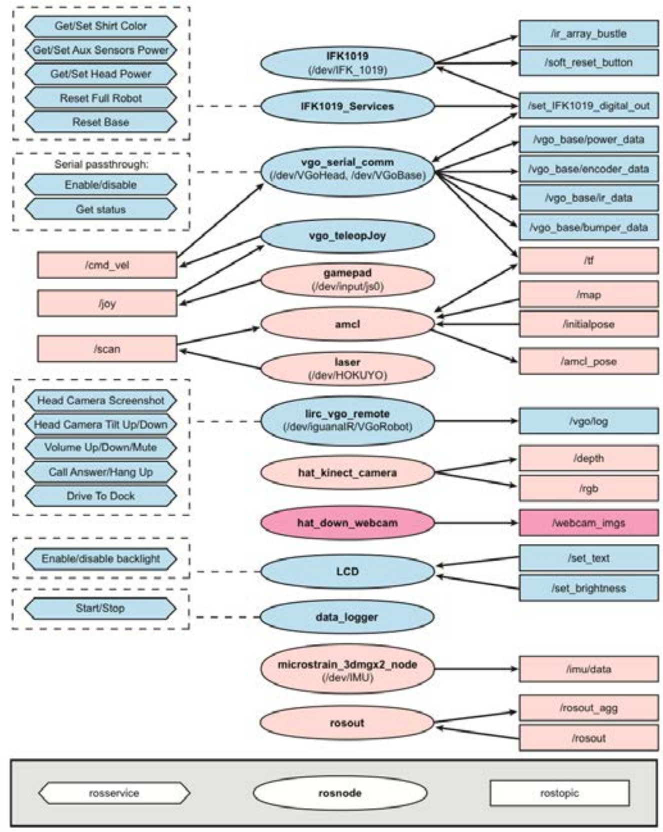

Fig. 7. Software diagram for Margo showing ROS services, nodes, and topics; directional arrows between nodes and topics indicate subscription and publication. The blue coloring indicates our custom software. Light pink indicates stacks, packages, and repositories provided by ROS; dark pink indicates contributions from the ROS community. (Best viewed in color.)

D. Discussion

We have replicated Margo’s design twice, and Margo has been used to conduct a Wizard of Oz study (n=12; see [31]). While the v1 prototype better satisfies our requirements, we have observed areas for improvement in the robot’s design. The COTS components and acrylic panels have nearly doubled the VGo robot’s weight, which has a number of side effects. The increased mass reduces the overall runtime of the system since the motors’ force output must be greater. We have observed a slight deformation of the wheels and difficulty turning in place. Also, Margo has a higher center of gravity than a standard VGo due to the location of the augmentations above and below the head. We are tuning the acceleration and deceleration to prevent rocking and sudden jolts with abrupt starts and stops; any jerkiness in the robot’s motion is amplified in the robot operator’s view since the camera placements are atop the robot’s head.

In Hugo’s next design iteration (v2), we will further reduce the robot’s weight by removing cutouts from the internal acrylic panels instead of perforation. Hugo will be upgraded with an ASUS Xtion Pro Live in place of the Kinect and a less expensive Hokuyo laser (URG-04LX-UG01), in addition to a customizable name tag for user identification, as per [24].

VI. Conclusions and Future Work

We have presented the design evolution of augmenting a standard VGo robot into a semi-autonomous social telepresence robot. Hugo (v0) and Margo (v1) are the culmination of two generations of iterative design. Hugo was a successful proof of concept; however, our v0 prototype did not have enough computational power to support the "go to destination" and "follow person" navigation behaviors, nor the level of control over the base to accomplish these behaviors. The lessons learned while developing Hugo lead to the formalization of requirements and design constraints for the next iteration. Margo's resulting design has resulted in a telepresence robot platform on which we have been able to develop our autonomous and semi-autonomous navigation behaviors.

In addition to implementing the "go to destination" and "follow person" navigation behaviors, our next step is to design a user interface for people with cognitive and motor impairments to support local (within camera view) and global navigation of a remote environment in a safe and socially acceptable manner. Our interface will utilize augmented reality techniques to visualize and overlay cues on the robot's video to provide in situ navigation assistance.

Acknowledgments

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