Design of a Low-Cost Platform for Autonomous Mobile Service Robots

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Abstract

Most current autonomous mobile service robots are either expensive commercial platforms or custom manufactured for research environments, limiting their availability. We present the design for a low-cost service robot based on the widely used TurtleBot 2 platform, with the goal of making service robots affordable and accessible to the research, educational, and hobbyist communities.

Our design uses a set of simple and inexpensive modifications to transform the TurtleBot 2 into a 4.5ft (1.37m) tall tour-guide or telepresence-style robot, capable of performing a wide variety of indoor service tasks. The resulting platform provides a shoulder-height touchscreen and 3D camera for interaction, an optional low-cost arm for manipulation, enhanced onboard computation, autonomous charging, and up to 6 hours of runtime. The resulting platform can support many of the tasks performed by significantly more expensive service robots. For compatibility with existing software packages, the service robot runs the Robot Operating System (ROS).

1 Introduction

Service robotics have seen an immense surge in the past decade. As robot capabilities improve, autonomous mobile service robots are being increasingly deployed for extended periods in a variety of environments, including homes, universities, offices, and commercial stores. Such service robots will be expected to be versatile, capable of performing multiple diverse tasks as finding a lost toy, retrieving medicine for an elderly patient, cleaning up after a party, escorting a visitor through an office building, or serving as a telepresence for a remote employee. Current robot platforms that are capable of performing multiple service tasks are typically either (relatively) expensive commercial robots (e.g., Willow Garage's Personal Robot-2 (PR-2), Rethink Robotics' Baxter, Savioke's Relay) or custom manufactured research robots (e.g., CMU's CoBots, Stanford's STAIR, Boston Dynamic's Atlas), which makes them inaccessible to many researchers and educators. In contrast, most mobile robot platforms for research are inexpensive (e.g, the TurtleBot 2, Adept MobileRobots' Pioneer, iRobot's Create 2), but typically are little more than mobile robot bases with limited onboard computation. Consequently, such research platforms are ill-equipped to serve as service robots without modification.

In this paper, we describe the design for a low-cost service robot based on the Turtlebot 2 open source platform.[1] Our design incorporates a variety of simple and inexpensive modifications that significantly enhance the TurtleBot 2, with the goal of transforming it into a indoor service robot capable of performing a wide variety of domestic or commercial tasks (as described in the next section). The modifications employ off-the-shelf components wherever possible for ease of construction, and the remaining custom parts can easily be ordered or 3D printed and assembled with a minimum of mechanical skill. In the near future, we intend to release the plans, STL files for 3D printing, and assembly instructions for the robot platform under a free license for education and not-for-profit research.

The TurtleBot 2 already provides a 14in (35.4cm) diameter mobile base with differential two-wheel drive, front bump sensors, cliff sensors, a 3D sensor (Microsoft Kinect or ASUS Xtion), a docking station for recharging, and a multi-level stack of mounting boards. Our design includes the following modifications to the TurtleBot 2 to create the service robot and provide it with significantly enhanced capabilities:

- **Enhanced onboard computation:** Instead of using the typical netbook for the TurtleBot, our design uses an Intel NUC for significantly improved computation. The NUC is powered by a commercial-off-the-shelf (COTS) external battery that recharges automatically when the robot is docked at the recharging station.
- **Shoulder-height 3D camera and touchscreen:** The service robot has a 3D camera and touchscreen mounted atop a 3ft (0.91m) mast, which raises the robot's height to approximately 4.5ft (1.37m) with minimal additional weight. The touchscreen serves both as a mechanism for users to interact with the service robot and as a telepresence screen. The 3D camera can be used for perception from a high vantage point or as the lens for telepresence.
- **Low-cost arm for manipulation:** We developed a low-cost arm (called the "DesiArm") that matches or exceeds

[1] http://www.turtlebot.com/

the specifications of significantly more expensive arms, including the ability to carry a 1.4kg payload and the support for modular grippers. The DesiArm can easily be assembled from 3D-printed PLA and laser-cut ABS plastic parts with the addition of a few COTS servos.

- **Improved perception:** Although the 3D sensor provided with the TurtleBot can be used for navigation, we incorporated a low-cost LIDAR for improved precision and reduced noise. We also added a speaker and microphone for speech communication.

The service robot runs the Robot Operating System (ROS), providing access to a large variety of software packages and easing software development on the platform. Figure 1 depicts our complete service robot platform.

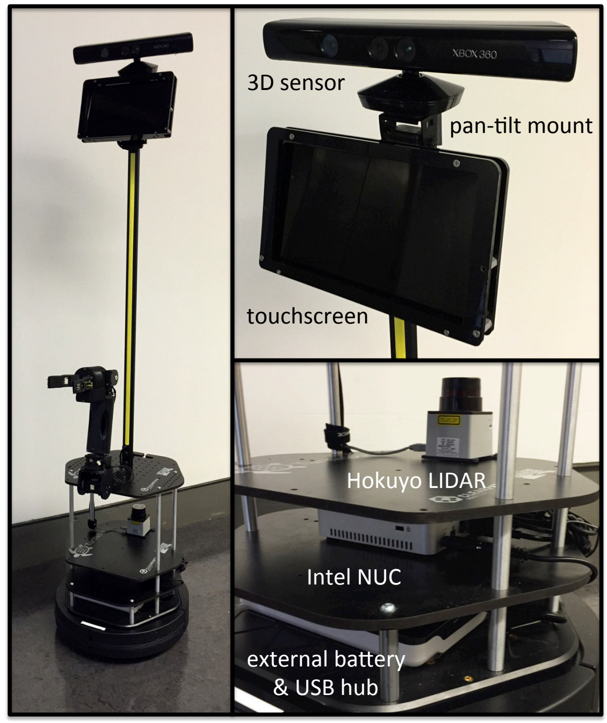


Figure 1: Our service robot platform (left), which adds a shoulder-height 3D camera and touchscreen (upper right), upgraded computation (lower right), improved perception, and an arm for manipulation to the widely available TurtleBot 2.

2 Service Robotics

Service robots are designed to assist people in their everyday lives [Computing Community Consortium, 2009] in a variety of environments, including residences, offices, commercial stores, and healthcare facilities. Commercial cleaning robots like the Roomba, Braava, and Neato can now be seen in many homes, and the presence of service robots will continue to grow as robot capabilities increase. Critically, service robots are designed to interact with people in typical human environments—we should not need to design the environments to the robots, as in many industrial settings.

Our particular focus is on *general-purpose* autonomous mobile service robots that are capable of performing diverse tasks (in contrast to specialized services, such as robotic vacuums) with limited user intervention. The duties of general service robots will vary widely: a hospital robot may be tasked with retrieving supplies, delivering samples, and tidying up conference rooms; a home robot may be responsible for cleaning, entertainment, and managing the medication of an elderly owner who lives alone; a disaster-relief robot may need to operate machinery, repair a pipe, or provide first aid to victims. Consequently, such robots need a variety of basic capabilities, including navigation, mapping, object recognition, scene understanding, and manipulation. In addition, service robots also need to supporting intuitive user interaction, such as via speech [Tellex *et al.*, 2011; Kollar *et al.*, 2013], web interfaces [Ventura *et al.*, 2013], or learning from demonstration [Coates *et al.*, 2008]. General service robots also face additional challenges from the integration of these diverse capabilities [Ng *et al.*, 2007] and long-duration deployments [Biswas and Veloso, 2013]. Competitions such as RoboCup@Home [van Beek *et al.*, 2015] help promote the development of versatile service robots.

3 Current Service Robot Platforms

In this section, we survey different robot platforms that provide capabilities needed for a general-purpose service robot.

3.1 Large Service Robots

Stanford's STAIR [Ng *et al.*, 2007] robot is perhaps one of the earliest comprehensive efforts at building a general-purpose home or office assistant robot; this concept has now evolved into a number of commercial platforms (Figure 2). One well-known large service robot is the Personal Robot-2 (PR-2) from Willow Garage. Extensive work has been done with the PR-2, but due to its high cost of approximately $400,000 USD, academic and private research institutions have been looking for cheaper alternatives with similar functionality. There are also a variety of less-expensive one-arm alternatives to the PR-2, including Fetch, KeJia, and PAL Robotics' TIAGo. The Rethink Robotics' Baxter robot provides a humanoid torso and compliant arms at a fraction of the cost of a PR-2 (approximately $20,000 USD), but does not come with a mobile base, making it suitable for manipulation tasks only. There are also custom service robot platforms without manipulators, such as CMU's CoBots [Biswas and Veloso, 2013].

There have been several recent efforts on developing service robots for hospitality and healthcare. The 3ft (0.91m) tall Savioke Relay robot is currently used for room service delivery in several hotels. It uses LIDAR, 3D sensors, and sonar to navigate autonomously through a pre-mapped environment, and has a touchscreen monitor for human-robot interaction. Research and commercial efforts have also made a push towards healthcare robotics [Robinson *et al.*, 2014] with the intention of meeting the needs of people with disabilities and the elderly, yielding such robots as Care-O-bot [Reiser *et al.*, 2013], Mobiserv [van den Heuvel *et al.*, 2012], and Mitsubishi's Wakamaru.

The DARPA Robotics Challenge (DRC) promoted the development of general-purpose robots for disaster relief, in

Figure 2: Example service robots: (1) Willow Garage's PR-2, (2) Rethink Robotics' Baxter, (3) Savioke's Relay, (4) PAL Robotics' Reem-C Robot, (5) Care-o-Bot [Reiser *et al.*, 2013], and (6) Universitat Bonn's Cosero.

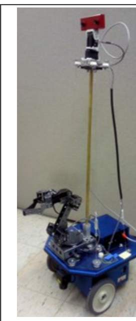
which robots had to compete in eight diverse tasks in human-engineered environments via semi-autonomous teleoperation with degraded communications. The DRC yielded a number of general-purpose bipedal humanoid robots, including Boston Dynamics' Atlas, Carnegie Mellon University's CHIMP, and KAIST's DRC-Hubo. However, the cost and custom nature of these robots prohibits their wide-spread use.

3.2 Low-Cost Service Robots

Although the robots described above are appropriate for commercial use or larger research groups, their expense limits their use in many education and research settings. Instead, educators and researchers often rely on low-cost robotic platforms (such as the Adept Pioneer P3-DX, iRobot Create 2, TurtleBot 2), modifying them as needed to support their application as service robots. The resulting custom robot is frequently brittle to maintain, limited in capability, and challenging for other groups to recreate. Table 1 shows several such low-cost service robots. There are also several recent commercial ventures to produce low-cost service robots without manipulators, such as Autonomous' Personal Robot (forthcoming as of June 2016), which has a mast-mounted display on a Kobuki base, and a variety of telepresence robots.

In contrast to these efforts, by building upon the standard TurtleBot 2 platform and focusing on modular easily-fabricated modifications, our goal is to produce a service robot platform that is highly capable, re-creatable, and affordable. This need for a standard low-cost service robot platform is also recognized by the RoboCup@Home league [RoboCup Federation, 2015]. Our hope is that researchers and educators will find this platform to be highly versatile, allowing them to focus instead on robotic applications instead of manufacturing custom low-cost hardware.

Table 1: Example low-cost mobile service robots.

	 **EL-E** **[Jain and Kemp, 2009]**	 **WUBBLE** **[Rebguns, 2016]**	 **ATOM** **[Makhal *et al.*, 2012]**
Mobile Base	Erratic base	Erratic base	custom base
Computation	onboard	onboard (laptop)	onboard (laptop)
Navigation	Hokuyo LIDAR	Hokuyo LIDAR	Microsoft Kinect
Vision	stereo camera	projector / stereo camera	2 HD cameras
Manipulation	Katana arm (5-DOF)	custom 7-DOF arm	two custom 4-DOF arms
ROS Compatible?	yes	yes	yes

4 Core Service Robot Platform

In this section, we describe the core components of the low-cost service robot platform, including the computational upgrades, improved perception, and the mast-mounted touch-screen and 3D camera. Collectively, these improvements significantly enhance the base TurtleBot 2 to serve as an effective indoor service robot capable of a variety of domestic and commercial tasks.

4.1 Mobile Robot Base

The service robot platform is built on top of the TurtleBot 2, a low-cost open-source robot that is widely used by educators and researchers. The TurtleBot 2 is built using a Yujin Kobuki mobile robot base, which includes front bump sensors, cliff sensors, differential steering, and a variety of ports for I/O and power. The TurtleBot 2 adds a multi-level stack of mounting plates on top of the Kobuki base to form a cylindrical robot 14in (35.4cm) in diameter by 16.5in (42cm) tall. As its primary sensor, the TurtleBot 2 uses either a Microsoft Kinect or an ASUS Xtion 3D sensor. The Kobuki base houses a 4,400mAh battery that powers the robot and 3D sensor, and recharges when the robot is docked. The TurtleBot is controlled via ROS, which runs on an attached computer.

4.2 Onboard Computer

We replaced the netbook used by the standard TurtleBot 2 with an Intel NUC mini-PC for significantly improved computation. The Intel NUC is a family of ultra-small (roughly 4.5in (11.5cm) square by 1.3–1.9in (3.3–4.8cm) thick, depending on the model) computers that runs on 12–19V DC power. We used the Intel NUC model NUC5i5RYK, which provided a Core i5 processor, integrated graphics cards, USB 3.0, and Bluetooth, with IEEE 802.11N WiFi added via a USB dongle. To power the Intel NUC, we used a COTS Poweradd Pilot Pro 32,000mAh external battery that could be recharged directly through the Kobuki base when the robot was docked. Both the computer and external battery pack are compact enough to be secured within the two lowest slots between the TurtleBot mounting boards. We also added a USB hub to expand the available connection ports of the NUC.

Upgrading to the Intel NUC enables the service robot to handle more computation onboard, including more complex perceptual processing, speech recognition, machine learning, and path planning. We also found the Intel NUC hardware to be much more reliable than the standard TurtleBot netbook. In combination with the external battery, the service robot with the Intel NUC was able to operate continually for approximately 6 hours (versus the approximately 2–3 hours of runtime for a Turtlebot 2 using a netbook). The only downside of using the Intel NUC instead of the netbook is the need for an external monitor, mouse, and keyboard for debugging.

4.3 Mast-Mounted Touchscreen and Camera

We increased the height of the robot by adding a 3ft (0.91m) mast of extruded 1in × 0.5in (2.5cm × 1.27cm) aluminum, raising the robot's overall height to approximately 4.5ft (1.37m) with minimal additional weight. Atop the mast, we mounted a touchscreen for user interaction with the service robot; the touchscreen could also be used to display video of a person in scenarios where the service robot is used for telepresence. We used a Google Nexus 7 tablet as the touchscreen, running a custom Android app for the user interface. We also experimented with using a 10in (25.4cm) Lilliput FA1014-NP/C/T touchscreen monitor, which required power from the external battery, but found the Nexus tablet to be a better choice due to its lower cost and integrated battery. The Nexus tablet can connect to the Intel NUC via either USB or Bluetooth serial communication; we chose the latter to simplify the configuration, with the tablet connected directly via USB to the external battery for recharging.

Above the touchscreen, the service robot has a mounted camera to provide a high level perspective for perception and as a lens for telepresence. This camera could be as simple as a webcam or more sophisticated, such as the Microsoft Kinect or ASUS Xtion 3D sensor provided with the TurtleBot, as shown in Figure 1. For additional capability, this camera can be mounted atop a pan-tilt mechanism, made from a pair of AX-12A Dynamixel Actuators and an ArbotiX-M Robocontroller. All cables for the touchscreen and camera were routed through the mast to the TurtleBot base.

4.4 Perception

In its standard configuration, the TurtleBot relies on a Microsoft Kinect or an ASUS Xtion 3D sensor for environmental perception. For improved precision in simultaneous localization and mapping (SLAM), we replaced the 3D sensor with a Hokuyo URG-04LX-UG01 scanning laser rangefinder placed on the TurtleBot base. This modification is optional, since the 3D sensor is effective for SLAM, but we did find that the Hokuyo LIDAR significantly improved mapping. The 3D sensor could either be used simultaneously from a low vantage point with the Hokuyo LIDAR, or relocated to serve as the camera atop the mast, as described in the previous section. We also added an optional USB microphone and speaker for speech communication.

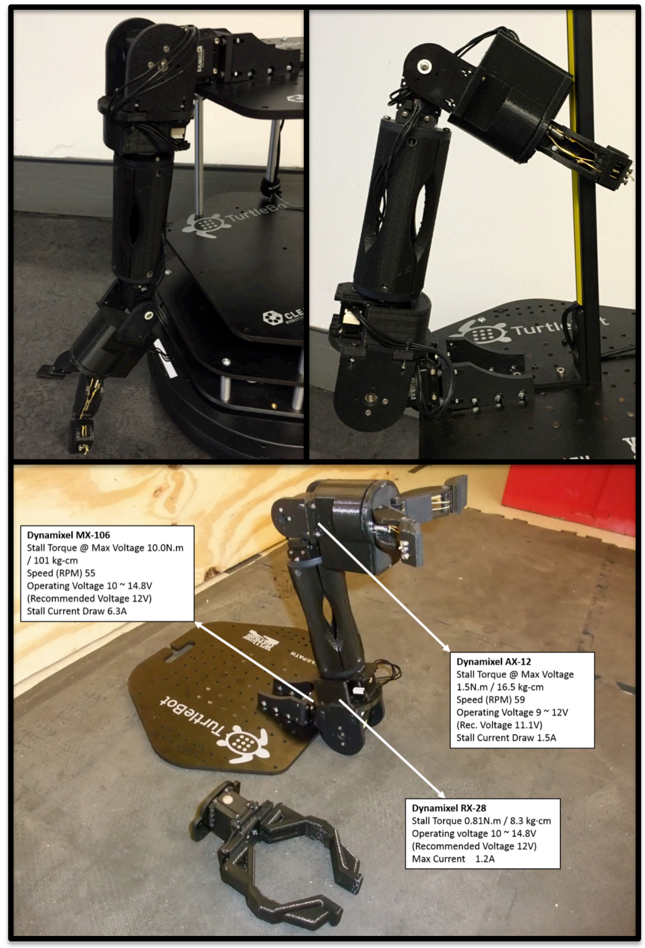


Figure 3: The low-cost robotic arm mounted on the service robot, which can pick up objects from the ground (upper left) or grasp the mast for a stable traveling position (upper right). The servos in the arm (bottom) decrease in expense and capability moving from the shoulder to the modular gripper.

5 Low-Cost Manipulator

Due to the practicality in adopting existing technologies, service robots often use expensive robotic arms designed for industrial applications rather than household or human-robot interaction tasks. Examples such as the Kuka LWR robotic arm and the Kinova Mico illustrate how expensive (over $16,000 without end effectors) and bulky these robotic arms can be. These arms also have high power requirements, making it infeasible to use an onboard power supply. Although some efforts [Quigley *et al.*, 2011] have been made to develop arms that cost under $5,000, the community still lacks accessible and modular robotic arms that do not demand experienced personnel to assemble and configure. Alternatively, many inexpensive robotic arms have very low torques and are unable to accomplish simple tasks such as lifting a filled water bottle. These low-cost arms are typically not modular, making them unable to easily switch end effectors for different tasks or to perform a variety of grasping techniques. Table 2

Table 2: Low-cost robotic arms, with our DesiArm highlighted in blue. This comparison shows that the DesiArm has a low cost and weight for the provided degrees of freedom, payload capacity, and capabilities. The arms are considered "human safe" if they have low weight and/or compliance to impacts.

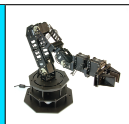
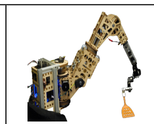
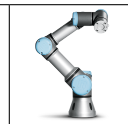
	 **PhantomX Reactor**	 **DesiArm**	 **WidowX Mark II**	 **[Quigley et al.]**	 **Dr. Robot Jaguar**	 **Cyton Gamma 1500**	 **Universal Robots UR3**	 **KUKA Youbot**
Estimated Cost	$550	$850	$1,500	$4,135	$8,750	$12,000	$23,000	$24,200
Degrees of Freedom	6	4	6	7	4	7	6	5
Total weight (Kg)	1.36	0.75	1.33	11.4	10	2	11	7.4
Max Payload (Kg)	0.6	1.4	0.8	2	4	1.5	3	0.5
ROS Compatible	yes	yes	yes	yes	yes	yes	yes	yes
Manufacturing material	ABS	PLA/ABS	ABS	MDF	aluminium	ABS	aluminium & plastic	aluminium
Modular Design	no	yes	no	no	no	yes	yes	no
Human Safe	yes	yes	yes	yes	no	yes	no	no

Figure 4: Mobility of the robotic arm.

provides is a comparison of various robotic arms.

To remedy these issues, we designed and developed the *DesiArm*, a low-cost, light-weight, modular robotic manipulator for service robots. It is ROS-compatible, costs approximately $850, and can be mounted on a Turtlebot 2 without any modifications to the robot. The arm has four degrees of freedom (including the gripper), and can be easily reproduced and assembled with minimal skill. Its modularity makes it easy to switch between different types of end effectors, based on the task and desired level of dexterity (Figure 5).

5.1 Manufacturing

We designed the arm using laser-cut ABS and 3D-printed PLA plastic parts. The choice of material was based on low cost, light weight, and ease of manufacturing, such that anyone with CAD software could reproduce the parts. We used the MakerBot Replicator for 3D printing and the Universal System PLS6 150D machine for laser cutting ABS. We used four Dynamixel servo-motors as actuators: the MX-106 for the shoulder lift, a RX-28 for the elbow roll, and two AX-12 servos for the wrist lift and the gripper. The total cost of the DesiArm is approximately $850 USD.

5.2 Modularity

Robotic manipulation often involves applications in which specialized end effectors are required. For simple pick-and-place applications, a parallel-jaw gripper can be effective, whereas for more advanced grasping or secure enveloping of an object, we might use a compliant gripper with more degrees of freedom. Some the robotic arms in Table 2 have their modularity limited to certain configurations, such as the use of less servos in the arm, but none of them allows for a quick change of end effector for various manipulation tasks.

In contrast, the DesiArm allows different grippers (Figure 5) to be attached to its wrist via a simple mounting plate (which is designed specifically for each end effector to match with the arm). For precise manipulation, a camera could also be easily integrated into the gripper (note that grippers in Figure 5 do not include cameras). We have not added sensing or haptic capabilities for the basic end effectors, assuming those can be easily adapted to it depending on the task.

5.3 Arm Control System

We use the Arduino Mega 2560 microcontroller to control the DesiArm, since its open-source nature makes it easy to acquire, program, and replicate. The servos receive command signals from the Arduino and it has external circuitry

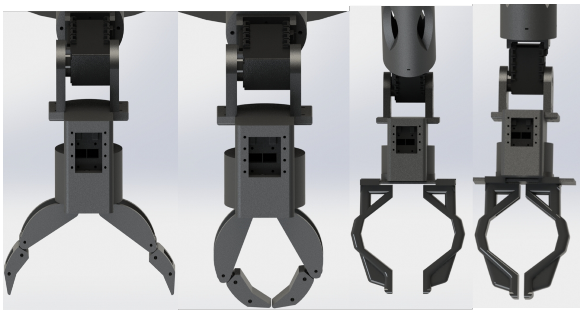


Figure 5: Compliant and parallel grippers attached to the robotic arm.

for powering the arm via the Kobuki base. We developed a ROS package to control the arm, providing simple listeners and publishers for controlling individual joints, and enabling easy integration of external sensors via the Arduino's analog and digital pins. Trajectory planning and simulation of the arm can easily be done using the MoveIt! software package.

6 Cost, Manufacturing, and Assembly

Our low-cost service robot platform is designed to be easily assembled from a collection of COTS components and easy-to-manufacture custom parts. All custom parts (i.e., the touchscreen frame, 3D sensor mount, Hokuyo LIDAR mount, and DesiArm) are made from either 3D-printed PLA or laser-cut ABS plastic, which can be fabricated within a few hours locally or ordered inexpensively from a 3D custom fabrication company. Given all the parts, the complete service robot can be assembled within a few hours, requiring only minimum mechanical skills. The communications and power wiring for the robot's components is given in Figure 6.

The total cost of the complete service robot platform, including the DesiArm, is estimated at approximately $4,450 (Table 3). The total cost can be reduced to approximately $3,450 by eliminating the Hokuyo LIDAR; a low-cost LIDAR (e.g., the RoboPeak RPLIDAR) could also be substituted instead. Further eliminating both the Hokuyo LIDAR and the DesiArm would bring the cost down to approximately $2,600. These estimates do not include shipping costs and assume that the TurtleBot 2 will be purchased unassembled.

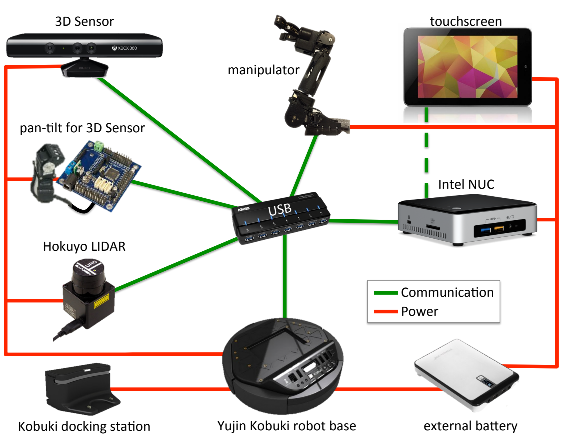


Figure 6: Power and communications wiring for the robot.

Figure 7: Prototype service robots designed as variations on our low-cost platform, developed by students in CIS 700 at the Univ. of Pennsylvania in Fall 2015. The middle and right robot also include a belt-driven elevator mechanism to raise the manipulator along the mast, using a coil spring to offset the arm's weight. These robots were used for a variety of tasks, including waiting tables at a simulated restaurant, object search and retrieval, and voice-based navigation.

Table 3: Estimated cost for the service robot platform.

Item	Estimated Cost
TurtleBot 2 Robot & Accessories	$1,350 USD
Onboard Computer	$750 USD
Mast & Touchscreen	$350 USD
LIDAR, Speakers, Microphone	$1,150 USD
DesiArm	$850 USD
Total	$4,450 USD

7 Conclusion

The proposed service robot provides a variety of capabilities necessary for a general service robot, while being easy to manufacture and requiring only a modest budget. Given the widespread availability of the TurtleBot 2 robot, many researchers and educators already have the foundation for constructing this service robot. This platform can easily be extended to other custom functionality as well, such as incorporating a pair of manipulators, or building a linear actuator into the mast to elevate the arm, as shown in Figure 7. As service robots become increasingly widespread, the need for low-cost and easy-to-acquire platforms is essential to ensure accessible research and education in this growing field.

Acknowledgments

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