Development of a Tele-Nursing Mobile Manipulator for Remote Care-giving in Quarantine Areas

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Abstract— **During outbreaks of contagious diseases, healthcare workers are at high risk for infection due to routine interaction with patients, handling of contaminated materials, and challenges associated with safely removing protective gear. This poses an opportunity for the use of remote-controlled robots that could perform common nursing duties inside hazardous clinical areas, thereby minimizing the exposure of healthcare workers to contagions and other biohazards. This paper describes the development of the prototype system Tele-Robotic Intelligent Nursing Assistant (TRINA), which consists of a mobile manipulator robot, a human operator's console, and operator assistance algorithms which automate or partially-automate tedious and error-prone tasks. Using off-the-shelf robotic and sensing components, total hardware costs are kept under $75,000. The system's capabilities for performing standard nursing tasks are evaluated in the simulation laboratory of a nursing school.**

I. Introduction

Healthcare workers like nurses, Emergency Medical Technicians (EMTs), and aid workers are exposed to highly infectious patients during disease outbreaks, such as the Ebola epidemic of 2014–2015. A major source of infection risk to these personnel is during the donning and doffing of personal protective equipment (PPE) and/or improper use of PPE. PPE must be donned before routine clinical duties involving patient contact or cleaning, and material and specimen transport. This challenge raises the potential for tele-operated robots to reduce infection risk to healthcare workers by minimizing personnel exposure to patients and hazardous clinical areas during routine care. Telerobotic approaches may also yield a host of other benefits in emergency medical response, including single-operator multiple-robot operation (fan-out), rapid switching between quarantine areas, and making more healthcare workers available at the site of an outbreak via remote teleoperation.

This paper describes preliminary work toward developing a tele-nursing robot. Version 1.0 of the Tele-robotic Intelligent Nursing Assistant (TRINA) mobile manipulator (Fig. 1) was developed to satisfy the following design objectives: the system should be human-safe, versatile, usable by novices, rapidly assembled, and relatively inexpensive. Conceptually, such a system should act as a surrogate for the human body to allow the operator to perform frequent caregiving activities in the quarantine environment. We also focus on light- to medium-duty manipulation tasks — such as cleaning, bringing food and medication, or pushing carts — rather than heavy-duty tasks like patient lifting. Building such a system poses a number of research challenges, such as developing hardware with sufficient strength, dexterity, perceptual sensitivity, and situational awareness to perform a wide range of functions, as well as software that provides a transparent, capable, and usable operator control interface.

To evaluate TRINA's capabilities, we identified twenty-six patient-care tasks frequently practiced by nurses, and carried out trials in a simulated patient room at Duke University School of Nursing. Results indicate that TRINA controlled by an expert operator can perform many routine nursing tasks including preparing and serving food, beverages and medicine to patients, moving medical devices (e.g., a medical cart, patient transfer bed, portable computer, walker, etc.), collecting medical devices (e.g. medicine bottles, syringe packages, IV tubing packages, etc.), operating storage cabinets, scanning bar codes on medical supplies, moving patients, and cleaning patient room debris. It can also take measurements from the patient room environment (e.g., temperature and humidity) using wireless sensors, and collect vital signs of conscious patients (e.g., blood oxygen saturation and blood pressure).

This paper also identifies areas of potential improvement. Most significantly, we find that highly dexterous, coordinated tasks are not possible with the current system, and teleoperation speed is much slower than human nurses performing these tasks in person. We conclude by identifying several possible directions of future research in the areas of dexterous manipulation hardware, sensor integration, semi-autonomous systems, and user interfaces that would help make the next generation of TRINA capable of a wider variety of tasks.

II. Related Work

Telepresence nursing robots have been widely used for patient-caregiver communication and for assisting in elder and disabled care in homes and hospitals, yet nursing robots that can physically interact with patients and modify environment still have very limited capability [1], [2], [3], [4], [5]. Clinical environments, especially during disease outbreaks, are chaotic and highly dynamic. Like surgical robots [6] or search and rescue robots in hazardous disaster sites [7], a nursing robot must be able to respond to a wide variety of unexpected tasks that arise in the course of patient care. They also must operate according to the judgement of human experts,

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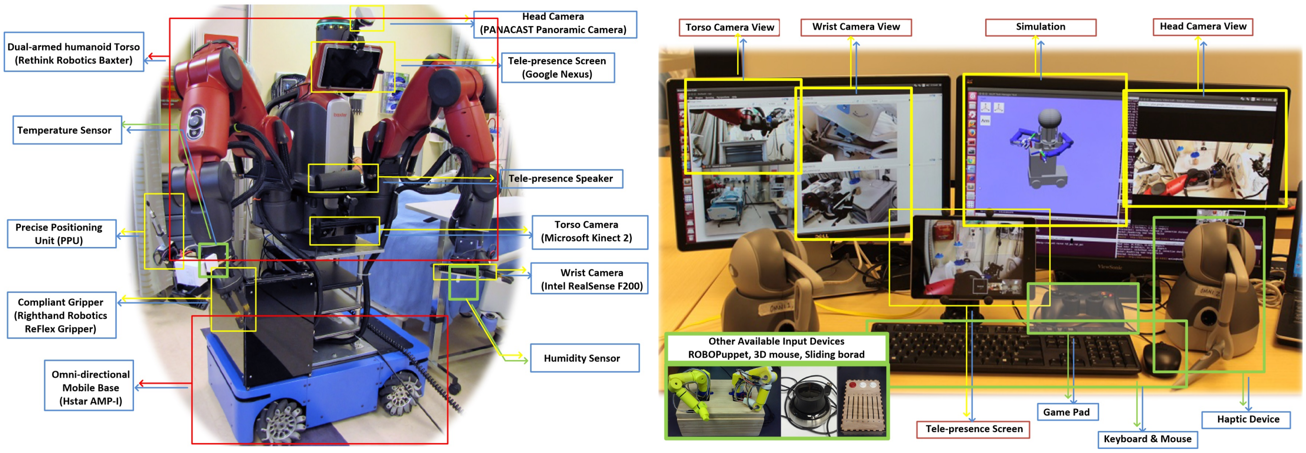

(a) TRINA robot, in a nursing simulation lab

(b) Operator console

Fig. 1: The two components of the Tele-robotic Intelligent Nursing Assistant (TRINA) system.

which necessitates a telerobotic approach. However, even with training and high-fidelity robots and input devices [8], it is generally difficult for human operators to directly teleoperate complex manipulation tasks. These challenges are amplified in tele-nursing. In addition, while the performance of surgical robots like the DaVinci surgical system is judged against manual laparoscopic tools, tele-nursing robots are judged against a human's entire repertoire of sensing, navigation, manipulation, and communication capabilities. Recent effort in mobile manipulation has improved the effectiveness and robustness of teleoperated nursing robot to perform dexterous manipulation in unstructured human environment [9]. The reaction of patients attended by teleoperated nursing robots, e.g., the comfort and trust of the operator has been experimentally evaluated [10]. However, before they can be practically deployed, the capability of the nursing robots still needs to be tested over a broader spectrum of frequently performed patient-caring tasks that involves intimate physical and cognitive human-robot interaction.

III. System

To span a wide range of human-like capabilities, TRINA has many degrees of freedom (26), a large workspace, and must operate over a range of strength and precision requirements from coarse pushing and lifting to fine manipulation. Furthermore, concerns about patient safety and robot approachability in close human-robot interaction add to the difficulties of system development and integration [11]. Thus, we developed TRINA with the following design goals:

- Mobility in a hospital room or ward (no stairs)
- Capability of light- to medium-duty tasks (<10kg forces)
- Safety in close proximity to and touching humans
- Facilitating audio/visual communication between a nurse and patient
- Non-expert operators can be trained in $<$ 1hr
- Continuous, 24hr operation
- Cost $<$ \$100,000

Our approach was to integrate several off-the-shelf components with the required capabilities. As a result of recent trends toward lower-cost robot hardware, the hardware components can be assembled for less than \$75,000. Overall, the robot is 1.7 m tall and weighs approximately 140 kg. The height of the robot is approximately the same as an American adult female, which we found to give the robot a less intimidating appearance.

We note that a field hospital setting in an outbreak scenario would indeed pose many more challenges, such as ability to tolerate brown-outs, and to cross uneven thresholds between flat flooring. Nevertheless, we decided to focus on the issues identified above, which are more representative of urban hospitals. We also do not focus on sterilization and waterproofing, which are left to be refined in future generations of the system.

The TRINA system has three major components:

1) A mobile manipulator robot.
2) An operator console.
3) A software system for the control and user interface.

This section describes the hardware and software components of the system in detail.

A. Mobile Manipulator Robot

The robot uses an off-the-shelf dual-armed humanoid torso (Rethink Robotics Baxter), an omnidirectional mobile base (HStar AMP-I), and three-fingered grippers (Righthand Robotics ReFlex grippers) on each hand to provide manipulation and indoor navigation capabilities. A telepresence screen, microphone, and speakers are provided to allow for bidirectional audio/visual communication between operator, patients, and other healthcare workers in the remote site. A variety of sensors are placed on the robot to provide visual feedback. The power cable roller has a 30 foot extension cord that retracts and locks at any length, which provides enough motion range to traverse a typical hospital room.

Patient safety arises from the use of compliant Series Elastic Actuators (SEAs) in Baxter's arms and compliant

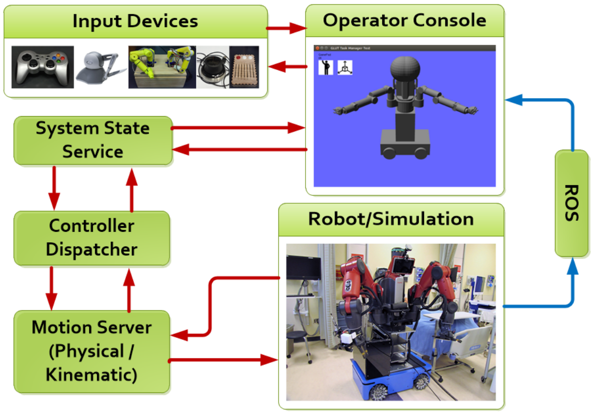

Fig. 2: TRINA software architecture.

fingers in the hands; this also improves system durability. However, safety comes at the cost of loss of precision, as the robot has approximately 1 cm of positioning error, and the hands have fairly bulky fingertips. To address some simple fine manipulation tasks like button pressing, we also mounted a custom-built Precise-Positioning Unit (PPU) a spherical manipulator on the robot's forearm, which can push targets with millimeter-level positioning accuracy.

The operator is provided with rich sensory feedback Fig. 1. Baxter comes with ultrasonic rangefinders to detect people around it. It can also detect collision via joint torque sensors. TRINA is also equipped with a visual sensor suite including a 180° panoramic camera (Panacast) on the head, a Microsoft Kinect 2 attached to the robot's chest and two Intel RealSense F200 3D cameras attached to the robot's wrists. All of the RGB+D cameras contribute to building 3D maps of the environment, which are provided to the operator's console. Four computers are mounted on the robot's chassis, one for motion control and three for vision processing.

B. *Operator's console*

The robot is remotely controlled from an operator console (see Fig. 1b) via a variety of input devices. Our expert operator's most effective mode of operation switches between a game control pad (Microsoft XBox gamepad) and dual haptic devices (Geomagic Touch). Other devices are also available, such as a mouse and keyboard, 3D mouse, and kinesthetic robot miniatures (RoboPuppet [12]).

The control / user interface allows the operator to control the robot via direct teleoperation as well as via semi-autonomous assistance. The user can directly teleoperate different parts of the robot — base, arm, or gripper — via joint or Cartesian position control to switch between predefined poses. Autonomous assistance functionality includes a variety of shared control modes, such as hand orientation or bimanual coordination control, as well as self collision avoidance. The operator's GUI lets the user switch between input modes, and displays the robot's cameras, 3D maps, and robot status.

C. *Software*

Fig. 2 illustrates the software architecture used in TRINA. Commands from **input devices** are relayed to the **operator console**, which communicates with the robot via the **system state service**. A **controller dispatcher** constantly listens to posted tasks, launches a task-specific controller, which then sends low-level commands to the **motion server**. Sensory feedback, including the videos of different cameras and a 3D display of the robot's cognitive map, are streamed to the operator console via the ROS (Robot Operating System) [13]. For off-line development, the physical robot can be replaced with a kinematic simulation at the level of the motion server.

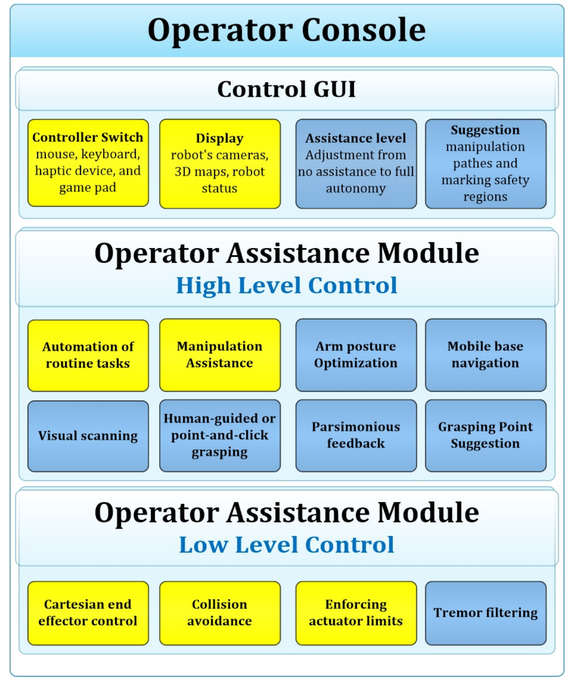

Fig. 3: The envisioned architecture of the operator console, with functions highlighted in yellow currently available.

An operator assistance module is provided to relieve users from tedious repetitive tasks, and to enable tasks that would be otherwise impossible to control via human hands. Fig. 3 demonstrates the assistance functions that the operator assistance module aims to provide, with currently available functions highlighted in yellow color. Low-level assistance uses existing software (e.g., the Klamp't motion planning package) for Cartesian end effector control, enforcing actuator limits, and collision avoidance.

Future work will address higher-level assistance, which should lower the learning curve, improve ergonomics, and improve performance. Plans include human-guided or point-and-click grasping, and automatic mobile base navigation. Interpolation between direct teleoperation and supervisory control can be provided with an adjustable autonomy interface [14] in which users choose the desired level of assistance.

IV. Experiment

A. *Procedure*

Our experiment was designed to test TRINA's capability on frequently practiced nursing tasks. First, a list of 26 common tasks was compiled with the help of nurse educators and shadowing of nurses in Duke Hospital, which covers 20%

Fig. 4: Twenty-six nursing tasks (Table I) were performed in a simulated hospital room. Tasks not feasible for the robot are shown by nurse demonstration.

of all possible nursing work (see Table I). Note that this list contains a wide variety of manipulation tasks with a wide range of objects' physical parameters, including small, light objects (straws), to deformable objects with intimate contact (packages and blankets), to heavy, bulky objects (a patient transfer bed).

Next, an expert operator was asked to tele-operate the robot in a nursing training environment in the Duke University School of Nursing (see Fig. 4). Tasks that consist of multiple subtasks were performed continuously from the beginning to the end. For all but the longest tasks, the operator made three attempts, and the average task completion time and success rate were recorded. An experienced nurse performed the tasks while wearing hazardous material coverings, including a face mask, goggles, and two layers of gloves.

B. Results

Table I shows the feasibility of the patient-caring tasks we tested on TRINA, as tested via up to three attempts on each task. Of the subtasks, 52 of 71 were completed successfully (e.g., without irretrievably dropping an object) at least once.

TRINA could not feasibly perform the following tasks: operating a remote temperature scanner (Task 18 and 19), taking sterilized supplies out of bags (Task 20), as well as operating a syringe (Task 21), attaching fresh IV bags (Task 22.2-22.5), and attaching a suction system (Task 23).

Fig. 5 compares the task completion time of the human nurse against the robot, and also provides the robot success rate in the form of "(number of success / number of attempts)". On average, the robot's task completion time is approximately 95x human completion time. Overall success rate in completed tasks was 78%.

V. Discussion

TRINA is most successful on gross manipulation tasks, such as serving trays of food, moving carts, disposing or moving medical equipment, and moving linens. However, the robot faces major challenges in some teleoperated tasks that are relatively simple for humans.

Part of this challenge may be morphological. Although the Baxter robot has 7-DOF per arm like a human arm, they are non-anthropomorphic in two respects. First, the elbow points "up" rather than "down" in the robot's rest configuration, and joint limits prevent it from reaching typical human elbow-down postures. Second, the intersection of the wrist axes is approximately 27 cm away from the palm of the gripper, which implies that wrist flexion produces a large movement at the gripper. Likewise, rotation about the palm or opening of the fingers causes a large movement of the wrist and elbow. We also note that the grippers are compliant and under-actuated, with only one motor per phalanx. Moreover, they only support pinch and power grasp modes, so dexterity and accuracy is much lower than a human hand. Our operator also found the following tasks to be particularly difficult:

- Inserting and unplugging tubes into receptacles or around nozzles.
- Opening packages of sterilized supplies.
- Turning knobs/rollers to control instruments.
- Pressing buttons to activate medical devices (e.g., temperature scanner).

Most of these issues are due to lack of fine dexterity when manipulating closely touched surfaces. Such capabilities will likely require the robot to possess millimeter-level accuracy and sub-Newton tactile forces. The fourth issue is an artifact of our choice of a gripper with compliant fingers. Due to the wide prevalence of buttons in clinical environments, for future versions of TRINA we plan to develop interfaces to operate the precise positioning unit (PPU) via supervised autonomy (e.g., clicking on a button on a camera feed causes the robot to autonomously press it).

The capabilities of TRINA 1.0 are most limited in:

- Precise, coordinated bimanual manipulation.
- Separating intimately touching objects (e.g., opening packaging, manipulating fabrics, and cluttered piles of objects).
- Precise fingertip positioning due to finger compliance.
- Lifting of heavy objects, particularly with unbalanced mass.

	Food preparation	
1	**Place objects on tray**	
1.1	Beverage cup	Yes
1.2	Closed food container A (10 cm)	Yes
1.3	Closed food container B (5 cm)	Yes
1.4	Medicine cup	Yes
2	**Insert straw into cup**	
2.1	Pick up straw	Yes
2.2	Insert straw	Yes
	Serving	
3	**Move tray from cart to table**	
	Table: Hospital Overbed Tray by EVA Medical	
3.1	Grasp tray	Yes
3.2	Lift tray	Yes
3.3	Move food tray from cart to table	Yes
3.4	Put down tray	Yes
3.5	Release grasp	Yes
4	**Move objects from tray to table**	
4.1	Beverage cup	Yes
4.2	Food container (10 cm)	Yes
4.3	Food container (5 cm)	Yes
4.4	Medicine cup	Yes
5	**Move tray with weight from cart to table**	
5.1	Grasp tray	Yes
5.2	Lift tray	Yes
5.3	Move tray	Yes
5.4	Place tray	Yes
6	**Handover to patient in bed**	
	Hospital bed by Hill-Rom Total Care Sport	
6.1	Beverage cup	Yes
6.2	Food container A (10 cm)	Yes
6.3	Food container B (5 cm)	Yes
6.4	Medicine cup	Yes
	Moving	
7	**Push Medical cart**	
	HermanMiller procedure/ supply cart	
7.1	Grasp on handle	Yes
7.2	Push	Yes
8	**Patient transfer bed**	
	Hausted APC All purpose chair stretcher	
8.1	Grasp on handle	Yes
8.2	Push	Yes
9	**Portable computer station**	
	Electronic health record on wheels by Enovate Medical Mobius Power	
9.1	Grasp on handle	Yes
9.2	Push	Yes
10	**Walker**	
	Invacare dual-release adult paddle walker with 5" wheels	
10.1	Grasp on handle	Yes
10.2	Push	Yes
	Collecting	
11	**Collect medical supplies into a container**	
11.1	Syringe flush bag A	Yes
11.2	Syringe flush bag B	Yes
11.3	Suction tube bag	Yes
11.4	Allergy liquid	Yes
11.5	IV tube bag	Yes
	Operating cabinet	
12	**Open and close cabinet drawer**	
12.1	Open	Yes
12.2	Close	Yes
	Barcode Scanning	
13	**Scan barcode on gauze bag**	
	TaoTronics TT-BS021 2.4 GHz Handheld Wireless USB Automatic Laser Barcode Scanner	
13.1	Pick up scanner	Yes
13.2	Scan	Yes
14	**Scan barcode on patient wrist**	
14.1	Pick up scanner	No
14.2	Scan	No
	Taking Measurement	
15	**Dip humidity sensor to liquid container**	
15.1	Dip sensor	Yes
16	**Take blood oxygen saturation**	
	iHealth wireless pulse oximeter	
16.1	Reach to patient	Yes
17	**Hand over wireless blood pressure cuff**	
	iHealth wireless blood-pressure monitor	
17.1	Grasp cuff	Yes
17.2	Handover cuff	Yes
17.3	Take cuff back	Yes
18	**Temperature - remote scanner**	
	Braun ThermoScan No Touch + Forehead Thermometer	
18.1	Center scanner light point and read	No
19	**Temperature - rub scanner**	
	Exergen temporal scanner infrared thermometer	
19.1	Rub across forehead	No
	Supply Preparation	
20	**Take sterilized supplies out of bag**	
20.1	Big syringe flush bag (peel)	No
20.2	Small syringe flush bag (peel)	No
20.3	Syringe needle bag (peel)	No
20.4	Gauze bag (peel)	No
20.5	Flush bag (tear)	No
20.6	IV bag (tear)	No
	Medical device / system operation	
21	**Syringe operation**	
21.1	Peel to open bag	No
21.2	Fill a flush	No
21.3	Dispose used syringes into container	No
22	**IV operation**	
	BD intravenous macrodrip administration set	
22.1	Take off old IV bag	Yes
22.2	Unplug IV tubes	No
22.3	Plug in IV tube to IV bag	No
22.4	Turn roller on IV tube	No
22.5	Hang new IV bag on IV stand	No
23	**Suction system operation**	
	Medivac suction canister system	
23.1	Unplug tubes from old container	No
23.2	Take suction container off	No
23.3	Set new suction container	No
23.4	Plug in draining tube to new container	No
	Moving patient	
24	**Lift patient arm**	
	Gaumard S205 Simple Simon Patient Care Simulator	
24.1	Grasp patient arm	Yes
24.2	Lift patient arm	Yes
	Cleaning	
25	Remove dirty linen	
	Angelica thermal hospital blanket	
25.1	Take off blanket	Yes
25.2	Put dirty blanket on cart	Yes
26	Remove patient room debris	
26.1	Move urinal container to cart	Yes
26.2	Move suction container to cart	Yes

TABLE I: Feasibility of 26 nursing tasks.

Stiffer, stronger, more precise hardware could address many of these issues, but at the expense of patient safety.

In discussions with the expert operator and novice trainees, they reported these challenges with learning the user interface:

- Learning which camera view to pay attention to for a particular task, and performing mental coordinate transforms when watching eye-in-hand cameras.
- Precise orientation control.
- Determination of a contact state change due to a lack of tactile sensation.
- Understanding the robot's combined position/orientation workspace, in particular joint limits and inverse kinematics singularities.
- Finger pre-shaping to grasp small or irregular objects.
- Tether management and situational awareness of obstacles around the mobile base.

To address these issues, we foresee two routes. Either the user interface could be made more transparent and immersive,

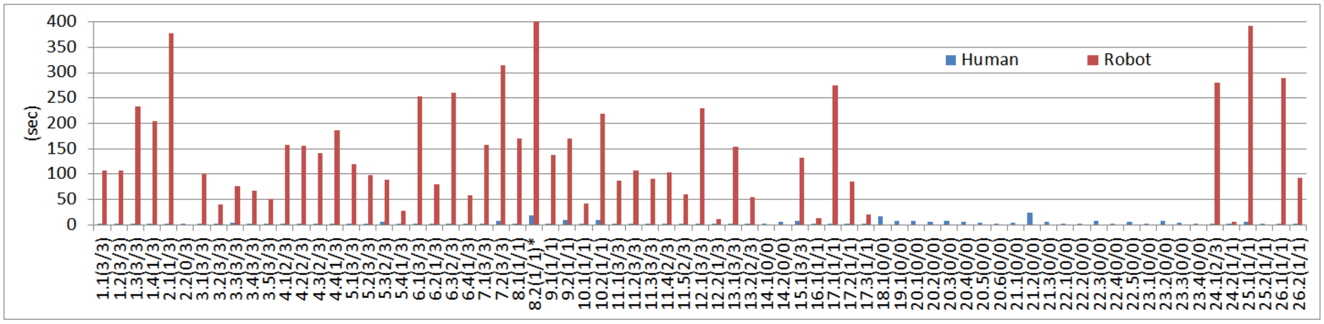

Fig. 5: Human and robot task completion time with the number of completed trials/attempted trials denoted in parentheses. Task 8.2 took 1,535 sec for robot.

with richer sensor feedback, or the UI could be designed with more pervasive operator assistance, putting the human in more of a supervisory role. It is an open question which direction will lead to improved performance.

VI. Conclusion

TRINA version 1.0 is a tele-nursing robot designed to assist human nurses and other clinicians communicate with patient, gather vital signs, and perform a wide range of manipulation tasks in a quarantine area, without being exposed to infectious diseases. TRINA was tested on twenty-six frequently practiced nursing tasks in a simulated patient room. An experienced operator successfully performed 52 of 71 subtasks, but at a rate 95x times slower than direct human performance. The robot was most successful at gross manipulation, and least successful at fine, dexterous manipulation.

Although these experiments suggest a promising start to making physical tele-nursing a reality, making progress toward the ultimate goal of 1:1 fidelity to the capabilities of the human body requires much additional research. For example, although the ReFlex hand is based on a winning design in the DARPA ARM-S program in 2013 [15], it is still insufficient to perform many fine manipulation tasks common in nursing and clinical care. Along with improvements in hardware precision, strength, and safety, control interfaces must also be improved, either via increased operator transparency and immersion, or via improved semi-autonomous control.

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