Robotic Assistant for Medical Applications

Sanjot Sunny Singh
Aeronautics and Astronautics
Stanford University
Stanford, United States
sanjot@stanford.edu

Faress Zwain
Aeronautics and Astronautics
Stanford University
Stanford, United States
fzwain@stanford.edu

Bryan Tiang
Aeronautics and Astronautics
Stanford University
Stanford, United States
tiang@stanford.edu

Hanvit Cho
Mechanical Engineering
Stanford University
Stanford, United States
hvcho74@stanford.edu

***Abstract*—The integration of robotics in emergency medical services has the potential to revolutionize patient care by enabling precise and reliable physical interactions. This research focuses on developing a robotic Emergency Medical Technician (rEMT) capable of performing critical tasks that require touch-based diagnosis and treatment. The primary challenge addressed is ensuring that the robot can safely and effectively interact with humans, performing tasks such as taking temperatures, applying pressure, and stabilizing limbs, which are essential for medical interventions.**

Our approach involves the development of advanced motion control and haptic perception capabilities. We implemented a compliance controller to maintain contact with dynamic objects and a Diagnosis mode to palpate patients and record stiffness data. The system uses a Kinova Gen 3, 7-DoF robot arm, equipped with a Bota SensOne force sensor and a Haply Inverse3 haptic device. These components enable the robot to perform precise and sensitive physical interactions, rendering haptic feedback to remotely located medical personnel.

Key results demonstrate the system's ability to maintain consistent contact force, detect varying stiffness levels, and provide accurate haptic feedback. The compliance mode ensures the robot can adapt to patient movements without causing harm, while the Diagnosis mode allows for detailed assessment of tissue stiffness, crucial for detecting abnormalities such as tumors. The success of this project showcases the potential for robotic systems to enhance emergency medical services by performing tasks that require high fidelity in touch and diagnosis.

***Index Terms*—haptic, medical, robot, control,**

I. Introduction

The growing integration of robotics in various fields has ushered in an era where robots are increasingly taking on roles that require close interaction with humans. One of the most critical applications of such technology is in the realm of emergency medical services, where the development of a robotic Emergency Medical Technician (rEMT) holds the potential to revolutionize patient care. This project addresses the essential scientific and engineering challenges necessary to create a rEMT capable of safe and effective interaction with patients through haptic feedback. [1] [2] [3]

A. Problem Statement and Importance

The primary challenge in developing a robotic EMT is ensuring that the robot can interact safely and effectively with humans, particularly in scenarios requiring physical contact. Human EMTs rely heavily on touch to diagnose and treat patients, performing tasks such as taking temperatures, applying pressure to stop bleeding, and stabilizing limbs. For a robotic counterpart to perform these tasks, it must be equipped with advanced motion control and haptic perception capabilities. The safety and reliability of these interactions are paramount, as improper handling could lead to patient injury or misdiagnosis.

B. Motivation

The motivation behind this research stems from the need to enhance the capabilities of robotic systems in healthcare settings. By enabling robots to perform tasks that require nuanced physical interactions, we can augment the efficiency and reach of medical services, particularly in emergency situations where timely and accurate intervention is critical. Moreover, developing these capabilities will inform the design of future robotic systems, setting a benchmark for performance and interaction standards.

C. Background

Haptic interaction refers to the sense of touch and the ability to perceive and manipulate objects through tactile feedback. In the context of human-robot interaction, haptics is crucial for tasks that involve physical contact. Current robotic systems often lack the sensitivity and control required for such interactions, necessitating the development of sophisticated methods to manage and interpret touch-based data.

D. Input and Output

The input to our system consists of various physical interactions between the robot and a simulated human subject. This includes tasks where the robot must approach, touch, and maintain contact with specific locations on the human body. The output of our system is twofold: first, the safe and controlled execution of these tasks, and second, the haptic data relayed to remotely located medical personnel. Specifically, our algorithm receives input in the form of contact interactions and uses compliant operational control and system identification techniques to output the perceived characteristics of the contact, such as stiffness and impedance, which are then communicated through a haptic interface.

In summary, this research aims to bridge the gap between robotic capabilities and human expectations in emergency medical scenarios. By focusing on the physical aspects of human-robot interaction and leveraging haptic feedback, we strive to develop a robotic EMT that can perform essential medical tasks safely and effectively, ultimately enhancing patient care and informing future technological advancements in the field.

II. System Overview

The developed system operates in two distinct modes: Compliance Mode and Diagnosis Mode.

A. Compliance Mode

The Compliance Mode is designed to maintain contact with dynamic targets, such as human limbs. This is achieved by implementing a compliance controller, which ensures that the robot can adapt to the movements of the object while maintaining a constant contact force. This is important for applications like practicing CPR, where consistent pressure.

B. Diagnosis Mode

The Diagnosis Mode enables the robot to palpate a simulated patient and measure the stiffness of various tissues. This mode involves recording force and displacement data to estimate the stiffness, which is then rendered through a haptic device to provide tactile feedback to the user. This allows the user to feel the measured stiffness, mimicking the diagnostic touch of a human EMT.

C. Hardware

The primary hardware component used in this project is the Kinova Gen 3 7-degree-of-freedom (DoF) robotic arm, as illustrated in Figure 1. Notably, joints 1, 3, 5, and 7 can rotate continuously without joint limits, while joints 2, 4, and 6 have joint limits to prevent self-collision.

Fig. 1. Kinova Gen 3

The end effector of the Kinova arm is equipped with a Bota SensOne force sensor, shown in Figure 2. This sensor is capable of measuring both forces and moments about the axes. The data from the Bota SensOne sensor is utilized to provide force feedback through the haptic device.

Fig. 2. Bota SensOne force sensor

The haptic device employed in this system is the Haply Inverse3, depicted in Figure 3. While the Haply Inverse3 can provide both position and orientation inputs, only the position input was used for the main experiments to render the tactile feedback accurately.

Fig. 3. Haply Inverse3 Haptic Device.

D. Software

The simulation and control of the Kinova robot were managed using OpenSai, a framework developed by the Stanford Robotics Lab. Redis was employed to facilitate efficient data transfer and communication between the Kinova robotic arm, the Haply haptic device, the Bota SensOne sensor, and the control system. This setup ensures seamless integration and real-time feedback across all components.

III. Methods

A. Data Communication

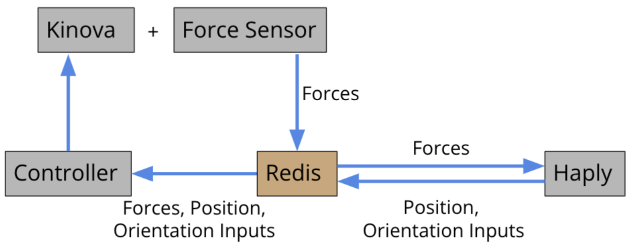

Fig. 4. State machine indicating how the data was transferred

Data communication in our robotic system is depicted in the state machine diagram in Figure 4. This closed-loop system ensures each component's crucial role in the accurate operation of the robotic arm, facilitating real-time data exchange and feedback essential for sophisticated applications in sensitive environments like medical settings.

1) Kinova Robotic Arm + Bota Force Sensor: The Kinova robotic arm, equipped with a force sensor, performs tasks requiring precise force application and sensing. The force sensor collects real-time data on the forces exerted on the robotic arm, ensuring safe interaction with the environment.

2) Controller: Programmed with OpenSai, the controller receives multiple inputs from the Redis database, including force, position, and orientation data. It uses this data to determine the movements for the Kinova arm, ensuring the desired conditions are met.

3) Redis: Redis functions as a real-time database, receiving force and joint data from the Bota and Kinova and transmitting this information to both the controller and the Haply device. It also handles incoming data regarding desired positions from the Haply haptic device, enabling quick synchronization between components.

4) Haply Haptic Device: The Haply Inverse3 haptic interface receives force data from Redis to provide physical force feedback to the user. This feedback is crucial in teleoperating applications, enhancing the operator's understanding of the remote environment.

B. Controllers

In OpenSai, the controllers were modified to account for the added mass of the Bota force sensor on the end effector by updating the URDF file.

1) Position Controller: The position controller commands the Kinova in joint space to a home position and saves the end effector's position in that configuration. Upon reaching the home position, the controller switches to task space control, enabling the end effector to move while maintaining a specific orientation in the world frame. The commanded position is the sum of the saved home position and the Haply's position. Additionally, a joint space task is set in the nullspace to keep the other joints as close as possible to the home position without interfering with the end effector's position and orientation. Forces from the Bota SensOne force sensor are sent to the controller, converted to the world frame, and then rendered by the Haply Inverse3. The controller also performs torque saturation to prevent excessive torques from being sent to the Kinova. A force scaling factor was applied to the Haply to reduce the magnitude of the rendered forces, with constant values for the x and y axes and variable values for the z-axis based on the end effector's positional error.

2) Force Controller: The force controller initially operates in position control mode but switches to force control mode upon detecting a force in the z-axis. In force control mode, the controller maintains a set force in the z-axis of the end effector while keeping the x and y axes in position control, controlled by the Haply. The end effector's orientation is set to remain perpendicular to the surface. Similar to the position controller, torque saturation is also implemented. The force controller can be configured to control the x and y axes in force control mode as well.

IV. Challenges

A significant challenge in our project was the integration and synchronization of various hardware components, necessitating the development of custom drivers for each device. Among these, the creation of the driver for the Kinova robotic arm proved particularly complex due to its intricate API.

Although orientation control was swiftly achieved in simulation, implementing this control on the actual Kinova hardware presented unforeseen difficulties. This issue was resolved by modifying the dynamic decoupling type for the motion task to bounded inertia estimates.

Instability was a notable problem for the positional controller when force feedback was transmitted to the Haply device. High-speed contact between the end effector and a rigid surface resulted in large reaction forces experienced by the user. To address this, we initially scaled down the forces transmitted to the Haply, which had the adverse effect of reducing the perceived stiffness of rigid objects. This was later mitigated by introducing variable force scaling. The variable force scaling was set to increase with the positional error of the end effector. The idea behind this being that rigid objects would resist the motion of the end effector and cause significant positional error.

Additionally, to achieve more stable contact with the end effector, we implemented an angular adjustment to its orientation. This modification enabled the force sensor to register forces as concentrated points rather than distributed over a broader area. By deviating from a strictly horizontal orientation and adopting a specific angular configuration, we significantly reduced the variability in force reception. This adjustment allowed users to experience a more realistic and controlled tactile sensation through the Haply haptic device, thereby enhancing the accuracy and reliability of the force feedback mechanism.

These combined efforts were essential in ensuring the system's stability and accuracy, thereby enhancing the overall user experience and the reliability of the force feedback.

V. Results

A. Force Control Experiment

In this experiment, we validated our controller's capability to utilize feedback from the Bota wrist sensor to consistently exert a specified force in the z-direction. The end effector was programmed to maintain a constant force of four Newtons in the negative z-direction (towards the ground), irrespective of external disturbances. Additionally, position control in the x and y directions ensured the end effector's horizontal coordinates remained constant. This setup simulates a medical palpation scenario, where the haptic interface user can move the end effector along a patient's body while maintaining a controlled contact force to detect stiff areas such as bone protrusions or tumors. Figure 5 illustrates the system's ability to sustain a constant z-force of 4 Newtons, despite disturbances in the z-position.

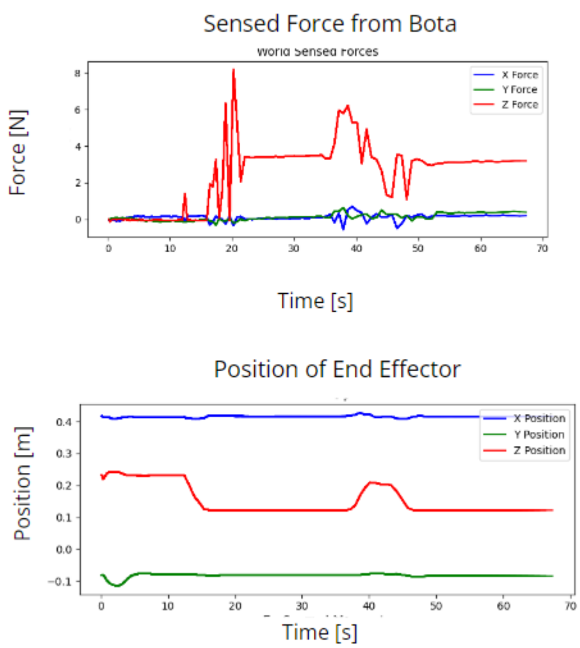

Fig. 5. Force Control Plotted Results.

B. Force Feedback for Detecting Object Stiffness

We designed a thin styrofoam casing over a rectangular plate containing three concealed stiff metal objects. The user, controlling the Haply device, could not see the locations of these objects and instead relied on force feedback to locate them. A similar setup was implemented on a humanoid mannequin to mimic human tissue stiffness variations. For instance, the sternum was particularly stiff compared to the softer pectoral muscles and abdomen. Figures 6 and 7 show the robot interacting with these stiff areas and the corresponding force readings and z-displacement data.

Fig. 6. Demonstration of Detecting Tumors.

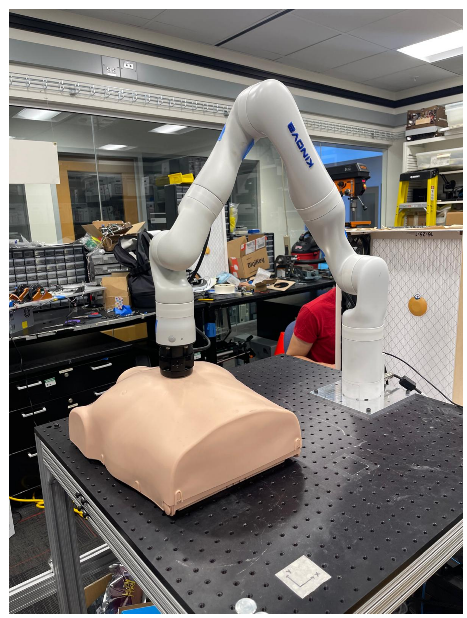

Fig. 7. Demonstration of Detecting Mannequin.

Figure 8 shows the force readings of the Bota sensor and the displacement of the z-direction of the end effector when the tumors are detected at different x and y coordinate locations. In future applications, this data could be used to create a stiffness grid resembling a patient, allowing medical professionals to playback the haptic rendering without needing live teleoperation.

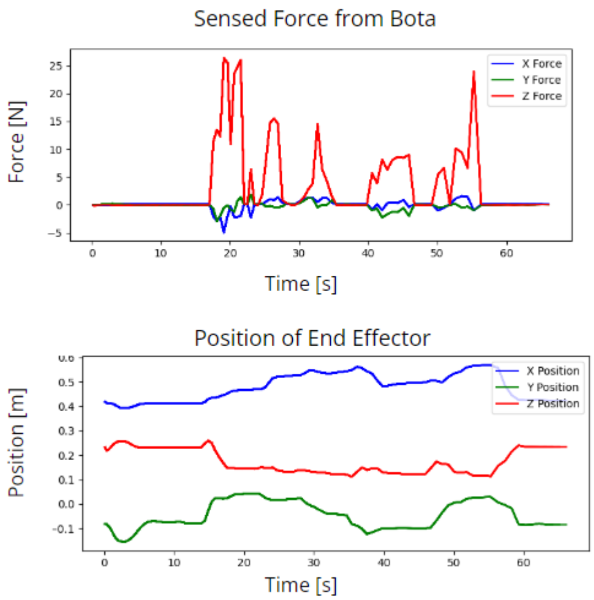

Fig. 8. Demonstration of Detecting Tumors.

C. Rendered Stiffness Grid in Simulation

We also developed a simplified stiffness map rendering in simulation using OpenSai. Three plates, modeled as linear springs with different stiffness constants (k), were created. By navigating along these plates with the Haply device, users could differentiate between the stiffness levels. Figure 9 shows a screenshot of the simulation, with plates color-coded by stiffness: red for the lowest, blue for medium, and green for the highest stiffness.

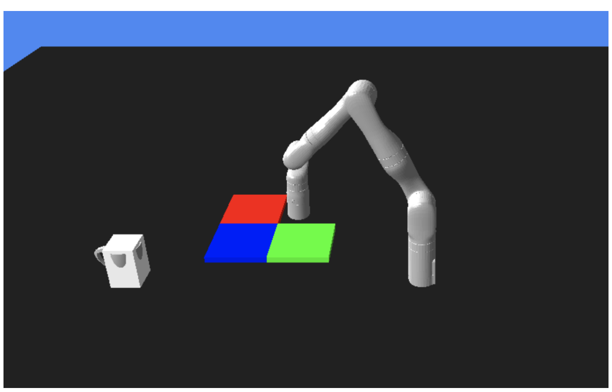

Fig. 9. OpenSAI Simulator simulating 3 different stiffness plates

The robot in the simulation served as a reference to indicate the plate being touched. The force rendered by the Haply was calculated based on the error between the desired and current end effector positions multiplied by the stiffness constant of the plate in contact, currently rendering stiffness only in the z-axis.

VI. Conclusion & Future Work

In this project, we successfully developed a robotic system capable of seamlessly interfacing with medical scenarios, focusing on creating a robotic Emergency Medical Technician (rEMT) that can perform precise and sensitive physical interactions. The system operates in two primary modes: Compliance Mode and Diagnosis Mode. These modes enable the robot to maintain consistent contact with dynamic objects and assess the stiffness of different materials through palpation.

Our demonstrations showcased the robot's ability to perform nuanced tasks that mimic human medical interactions. The force control systems effectively maintained predetermined force levels despite dynamic conditions, while the haptic feedback system allowed users to accurately perceive varying stiffness levels. These capabilities are crucial for tasks requiring high fidelity in touch and diagnosis, such as detecting abnormal tissue stiffness in patients.

Despite these successes, several challenges need to be addressed to enhance the system's performance and applicability in real-world medical settings:

1. **Zero-Moment Control Implementation:** Although zero-moment control works in simulation, its implementation on actual hardware remains a challenge. Future efforts will focus on integrating zero-moment control to enhance the stability and accuracy of the robot's interactions, ensuring precise orientation and positioning.

2. **Mitigation of Vibrations on Rigid Surfaces:** High-speed contact with rigid objects can cause vibrations in the force feedback. Refining control algorithms to dampen these vibrations is essential for achieving stable and reliable touch during live teleoperation.

3. **Integration of Vision Systems:** To improve operational safety and efficiency, we plan to integrate vision systems that create slow zones and no-fly zones, preventing the robot from entering hazardous areas or operating too quickly in sensitive zones.

4. **Accuracy Testing of Stiffness Measurements Using Force Control:** We aim to test the accuracy of using force control for stiffness measurements. Programming the robot to automatically record stiffness values for later rendering is crucial for validating the reliability of tactile feedback, which is critical for medical diagnostics.

Addressing these challenges will advance our robotic system's capabilities, making it a more effective and reliable tool for emergency medical services and other healthcare applications.

Acknowledgments

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We acknowledge the specific contributions of each team member:

- **Sunny Singh:** played a primary role in setting up the hardware environment and establishing the foundation for the software programs essential for force feedback.
- **Faress Zwain:** was key in creating control algorithms for consistent robot-object interaction and implementing error-handling procedures.
- **Bryan Tiang:** led the development of software, including controllers and simulators, improving system interface and data processing for real-time feedback and control.
- **Hanvit Cho:** led the setup of the force sensor on the robot's end effector and contributed to programming the robot's controller, including force feedback mechanisms.

We also acknowledge the resources provided by Stanford University, including access to state-of-the-art robotics labs and computing facilities. We are especially grateful for the funding and support from Rana Zarrin and the Honda team, which were essential in realizing our project goals.

REFERENCES

[1] F. Conti, J. Park, and O. Khatib. Interface design and control strategies for a robot assisted ultrasonic examination system. In *Experimental Robotics: The 12th International Symposium on Experimental Robotics*, pages 97–113. Springer, 2014.

[2] O. Khatib. A unified approach for motion and force control of robot manipulators: The operational space formulation. *IEEE Journal on Robotics and Automation*, 3(1):43–53, 1987.

[3] O. Khatib, L. Sentis, and J.-H. Park. A unified framework for whole-body humanoid robot control with multiple constraints and contacts. In *European Robotics Symposium 2008*, pages 303–312. Springer, 2008.