16

RobinHand Haptic Device

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Abstract

This chapter presents the stages of the design process and the working principle of the RobinHand control device adapted for the needs of the STIFF-FLOP project. The chapter also presents the concept and method of transferring tactile sensations (force and vibro-tactile feedback) from a real device or virtual reality to the user. The authors also discuss the structure, the working principle, and the application of the interface. A number of prototypes are developed and presented along with a brief description of their structure.

16.1 Introduction

There is a great potential in using medical robots in surgery as they offer increased precision and enable minimally invasive access to the operating field. Medical surgery typically makes use of tele-manipulators, with a human who takes decisions concerning the motion and tasks to be performed on the one side of the robot and a surgical instrument executing tasks in the working space inside a patient's body on the other side. Control of the medical robots takes place in real time. The trajectories are defined typically in the Cartesian space or in the configuration space variables (coordinates). The main problems involved in controlling a tracking motion include ensuring the required precision and stability of motion.

While designing a control device and a control algorithm, it is necessary to take into account variable working conditions that result from the performance of different tasks [1–3]. The simplest control system may be applied when the motion controller's kinematics and the robot's kinematics are similar; in this situation, the motion of the motion controller directly corresponds to the robot's motion. Optimal kinematics of the manipulator (slave) typically differs from the kinematics of the motion controller (master). It requires calculations of the control system based on forward and inverse models of the tool robot and the motion controller. The system may be equipped with detection, processing/conversion, and transmission modules, which relay feedback information, reflecting the interaction of the tool with objects in the operating field to the operator in a number of ways including force feedback, optical, thermic, and vibratory sensations. Both signals carry the information about the actions of the operator [4–6]. In surgical robots, a lack of effective force feedback makes the surgeon's work significantly more difficult. The surgeon can rely only on visual feedback to safely interact with the body's tissues. In order to eliminate the deficiencies resulting from this type of control, haptic (Greek: háptein – attach, grab) motion controllers are developed, which allow controlling the robot while providing the operator with subjective sensations of direct contact with the manipulated object at the same time [5–9].

16.2 The User Interface RobinHand

For the purposes of the STIFF-FLOP project, three versions of the motion controller called *RobinHand* have been developed and adapted. The first of them was developed and made in 2015 by a group led by Krzysztof Lis. The *RobinHand H* motion controller has three degrees of freedom and does not offer any feedback. This motion controller is intended to control the visual tracking robot and manipulating the robot in a virtual 3D reality. *RobinHand H* interface is presented in Figure 16.1 [4, 5].

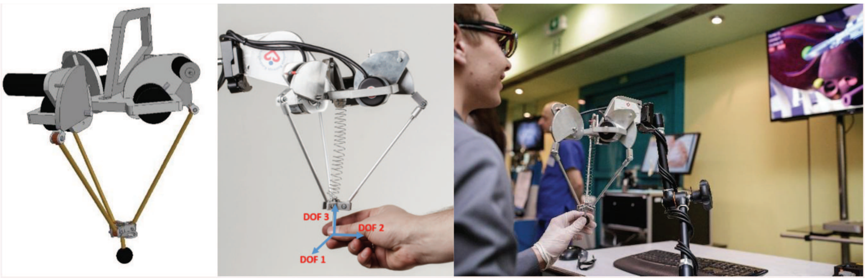

Figure 16.1 Haptic *RobinHand H*: CAD model, degrees of freedom, and system operation in a virtual 3D environment [5].

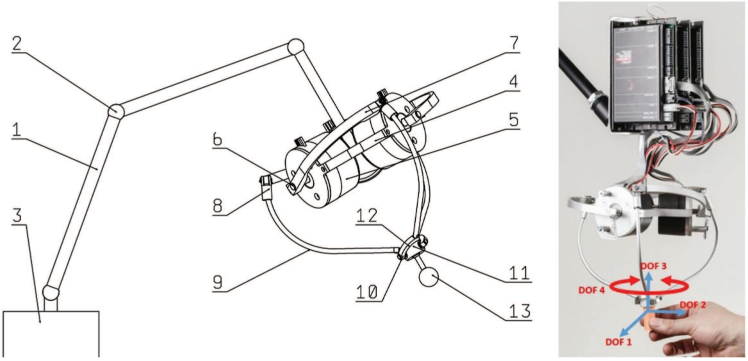

Figure 16.2 A perspective view of the manipulator *RobinHand F* [5, 10].

The second version – *RobinHand F* is equipped with drives which offer force feedback in the first three degrees of freedom (DOF 1–3) and the third version with a rotational degree of freedom (DOF 4) without force feedback (Figure 16.2).

In this project (Figure 16.2), the manipulator comprises a fixing arm (1) with any number of joints (2) enabling angular deflection and adjusting individual parts of the mounting system. The fixing arm (1) is mounted to the base (3) in any way on the one side, and to the fixed platform (4) on the other side. There are three motors with built-in encoders (4) mounted on the fixed platform (5). Lines comprising rotational axes of shafts (6) of the three motors (5) intersect at one point at an angle of 120°. There are first arched connectors (7) fixed on the shafts (6) of the motors (5) with an angle range of 90°. The first arched connectors (7) are rigidly connected with their first ends to the shafts (6) of the motors (5), thus enabling their rotation, which results in an angular deflection of the second end of the connectors (7). The second ends of the first arched connectors (7) are connected by means of joints (8) with three degrees of freedom with the first ends of the second arched connectors (9). The three degrees of freedom are a result of using a pivot-type joint (8) between the first arched connector (7) and the second arched connector (9). The angle range of 90° of the first arched connectors (7) requires such a shape of the connector that the rotational axis of the joint (8) in relation to the connector (7) is at an angle of 90° in relation to the rotational axis of the shaft (6) (a top view of the fixed platform with an indicated working angle is presented in Figure 16.3). The second ends of the second arched connectors (9) have transverse arched arms (Figure 16.4) and are connected with the arms by means of a pivot joint (10) to a mobile platform 11. On the mobile

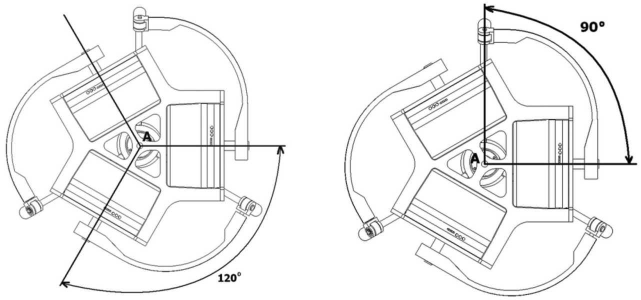

Figure 16.3 A top view of the fixed *RobinHand F* platform with an indicated work angle [10].

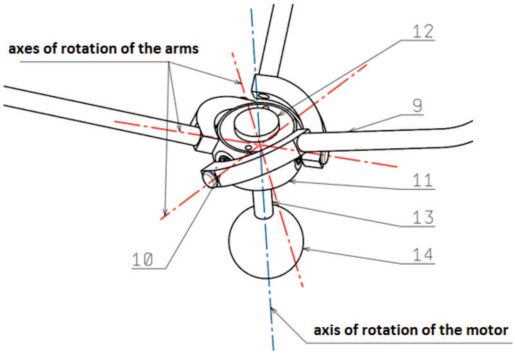

Figure 16.4 A perspective view of the mobile platform with indicated rotational axes *RobinHand F* [10].

platform (11), there is a motor mounted inside with a built-in encoder (12). A control knob (14) for the operator or alternatively other sub-assemblies of the controller allowing the operator to increase the number of degrees of freedom is mounted to the shaft (13) of the motor (12). The rotational axes of the second ends of the second arched connectors (9) intersect at one point on the line comprising the rotational axis of the shaft (13) of the auxiliary motor (12) mounted on the mobile platform (11). Figure 16.5 shows the kinematics of motion of the individual kinematic pairs.

The STIFF-FLOP project was evolving along with the growing experience of the FCSD team. In the next version of the motion controller, the design of the knob (held by the operator while using the controller) was modified. *RobinHand L* version was adjusted to the needs of the project, offering 7 DOF, where the first three degrees used force feedback (Figure 16.6).

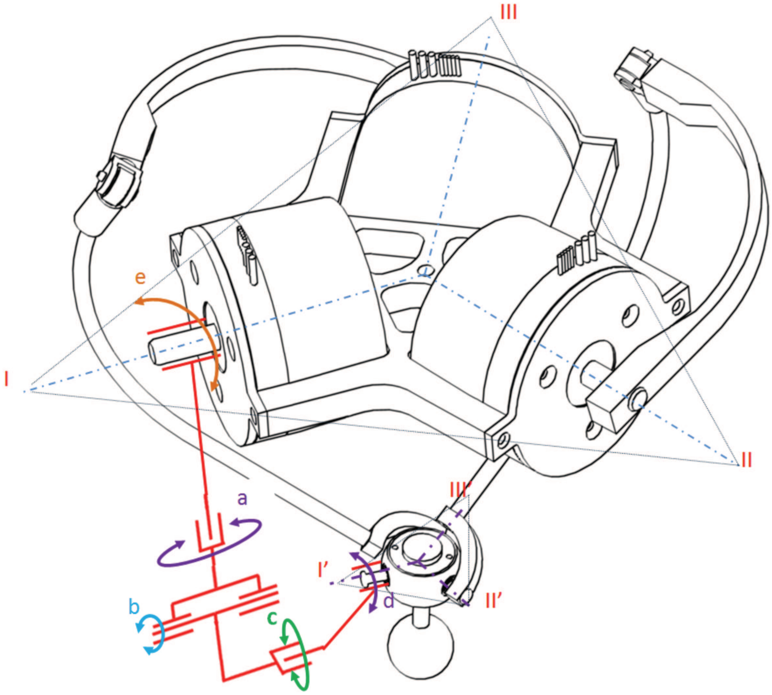

Figure 16.5 A perspective view of the manipulator with indicated kinematics of motion of individual kinematic pairs *RobinHand F* [10].

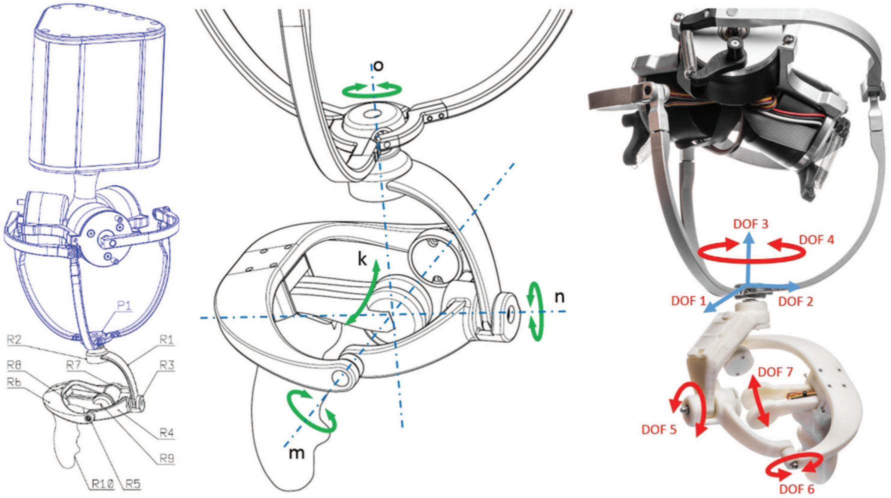

Figure 16.6 *RobinHand L* haptic platform.

The additional degrees of freedom allow controlling the tools/robot with additional articulated joints. The ergonomics of the manipulator was improved by adjusting it to the operator's hand so that the lines going through the articulated parts cross each other at the same point, just between the fingers of the operator. This solution made the handling of the controller more intuitive. To execute the construction of such a sophisticated form, it was necessary to implement the most advanced 3D printing technology as well as systems of joining different modules (metal-plastic and metal-composite). The use of rapid prototyping (FDM 3D printing with PC-ABS material) resulted in minimizing the weight of the component manipulated by the operator. This solution also contributed to reducing the time needed to develop other prototype versions to find the best match with the operator's needs [11]. Figure 16.6 shows the components made with R1, R4, R6, R9, and R10 methods. The electronics behind the control system were improved. This motion controller was made in two versions: mobile – fixed on the articulated arm (Figure 16.7a) and in a version which allows installation on the brand-new version of the STIFF-FLOP control console (Figure 16.7b). The above solutions are legally protected in the form of patent applications: US 9393688, EP 2990005, PL W.124541 [10, 12, 13]. The controller is currently used to

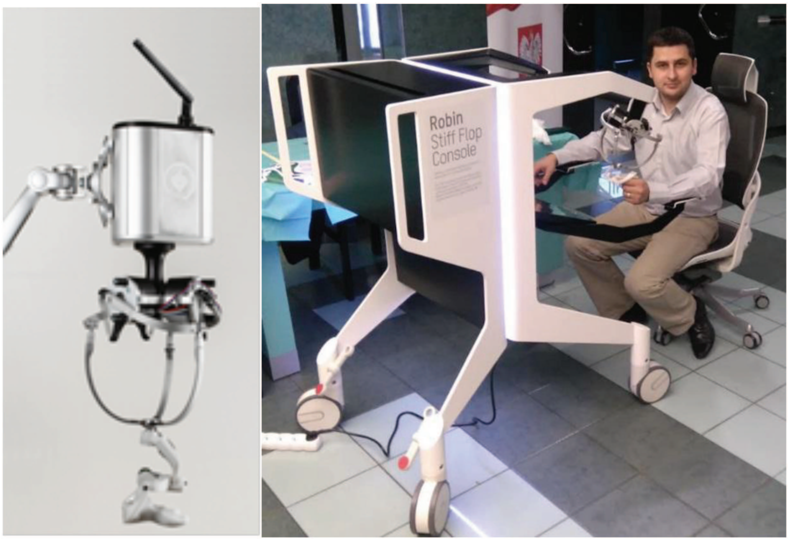

Figure 16.7 Haptic *RobinHand L* – mobile version and the version adapter for the STIFF-FLOP console.

control the *Robin Heart "Pelikan"* robot in Foundation Cardiac Surgery Development (FCSD) in Zabrze [14].

16.3 RobinHand in STIFF-FLOP Project

The implementation of the user interface RobinHand has been performed exploiting requirements and specifications based on a previously conducted Robin Heart project. Most importantly, we incorporated digital mapping allowing free movement of the surgeon's hand and providing haptic feedback to the surgeon's palm, relaying back the interaction of the robot arm's working tip with the inside of the abdominal cavity of the patient.

The movement performed by the operator's hand is captured by encoders in the haptic RobinHand unit. Information from the encoder is processed by a microcontroller (STM32) and is sent in the form of Cartesian coordinates to the microcontroller which operates the pressure valves used to control the robot arm's movements. Feedback information from the STIFF-FLOP is collected from the pressure sensors connected to each channel and is used to calculate the position error and in turn to bring (in order to bring) the arm to the desired position in the X, Y, Z space (Figure 16.8).

In order to check the haptic *RobinHand* functionality, FCSD tested and evaluated the integrated haptic console system (Figures 16.9 to 16.12). The system was launched and tested with force feedback acting both on the haptic console and the vibrating sleeve described in Chapter 14 [3, 15].

The integrated system used for the testing comprises the following:

- Two pneumatically operated robot arms equipped with both lateral flexi force sensor as well as frontal and circular lateral pressure sensor;
- A completely integrated system composed of the FCSD *RobinHand* haptic, a haptic vibration sleeve, and a soft robot arm inspired by STIFF-FLOP (made from Dacron –polyester fiber vessel prosthesis and Ecoflex – 30 silicone).

16.4 Operator–Robot Cooperation through Teleoperation and Haptic Feedback

In all the remote tests, a user (at the master site) provided input signals through a user-input console. The provided inputs were then transmitted via the Ethernet to a remote "receiver site" where the signals were used to actuate and control the STIFF-FLOP arm. In some of the experiments, force

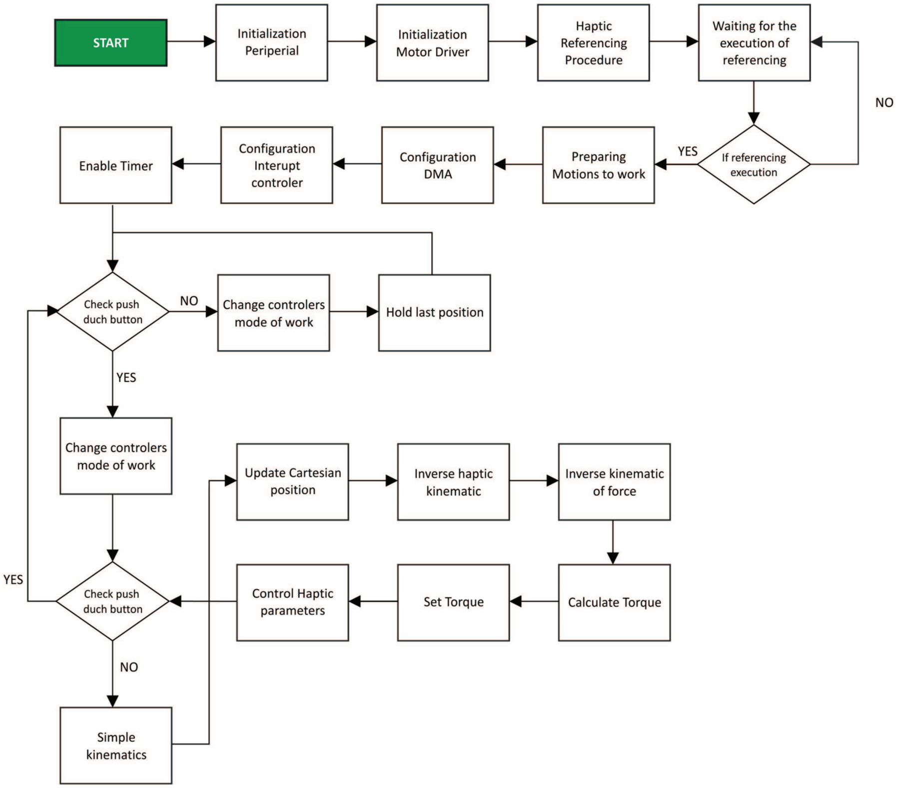

Figure 16.8 *RobinHand* manipulator and main program loop.

and tactile sensor information was collected at the robot arm–environment interface and fed back to the master system providing the user with appropriate resistance to their input movements when using the user input console, achieving tactile feedback.

16.4.1 Telemanipulation FCSD-UoS RobinHand H

The main specifications of this experimental study can be summarized as follows:

- Access to a private network can be obtained by using VPN server and FCSD infrastructure provided by a public network such as the Internet (University of Surrey, Dr. Tao Geng).

Figure 16.9 The FCSD flexible manipulator inspired by STIFF-FLOP; the construction and the first test of manipulator with pressure and force sensors.

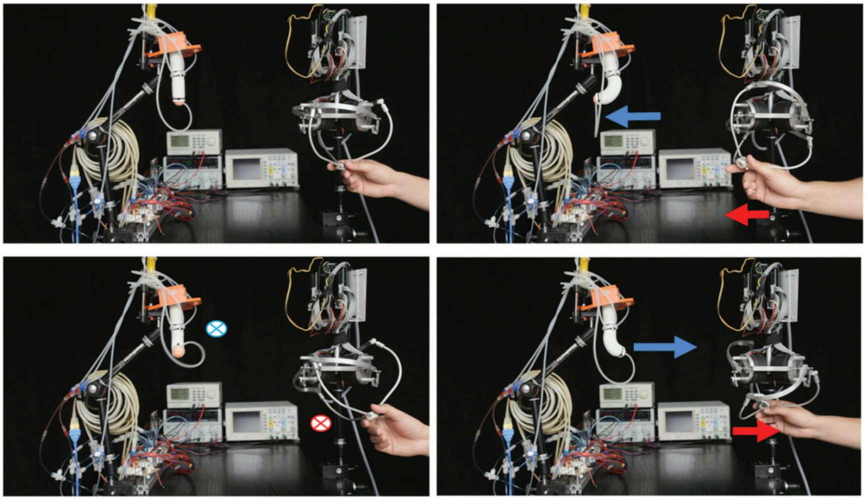

Figure 16.10 The pneumatic driving test of the haptic system and flexible manipulator.

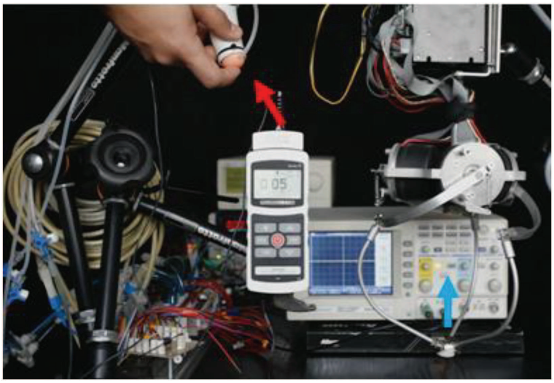

Figure 16.11 The feedback evaluation test of the haptic system and flexible manipulator.

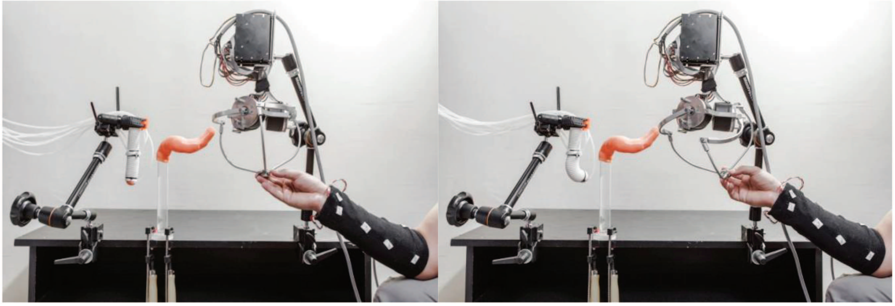

Figure 16.12 The full haptic – flexible manipulator – vibration sleeve test of feedback.

- A computer from FCSD operates as ROS_MASTER and publishes Delta coordinates X, Y, Z via the ROS topic, "/ sf_delta_pos." After that, the computer receives the published coordinates from Surrey University and converts those into the movement of the STIFF-FLOP arm (Figure 16.13).

In the conducted experiments, the commands from the FCSD haptic system FCSD Delta were sent to the robot controller at UoS actuating the pneumatic actuators of one STIFF-FLOP arm module. The test was conducted successfully and represents an important step in the development cycle of STIFF-FLOP. As shown in Figure 16.13 and on the video (available at the repository), when the Delta Haptic at FCSD is moving, the robot arm at UoS moves accordingly.

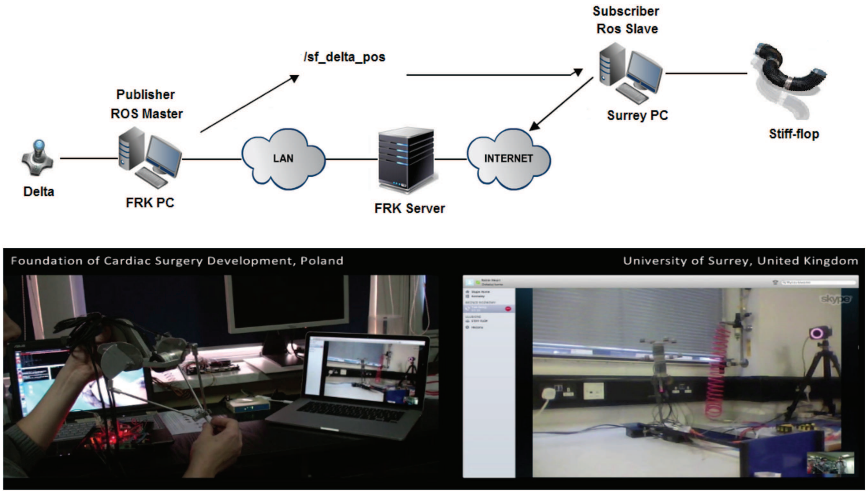

Figure 16.13 FCSD Haptic *RobinHand H* connection to the ROS system; performing telemanipulation between FCSD (at left) and UoS (at right).

16.4.2 Telemanipulation FCSD-PIAP RobinHand F

The first testing of the STIFF-FLOP control feedback console was carried out via remote connection between FCSD (Zabrze) and PIAP (Warsaw). Figure 16.14 shows the Haptic *RobinHand F* manipulator during the connection, prepared for the STIFF-FLOP robot – in this case, the console was equipped with a force feedback mechanism. The console's design is based on the keypad Delta (i.e., parallel kinematics). The Delta man–machine interface allows three DOF positions in space.

It is possible to increase the number of degrees of freedom to a maximum of seven DOF. In order for this device to work as described, forward and

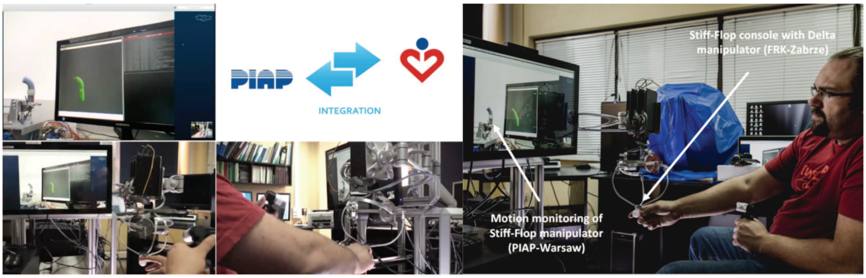

Figure 16.14 Remote telecontrol of STIFF-FLOP arm during FCSD-PIAP connection via the Internet (VPN).

inverse kinematic models are required. The main haptic algorithm enables users to touch, feel, and manipulate STIFF-FLOP modules through the force-feedback Delta device. The Delta parallel manipulator has large force reflection and high stiffness due to its parallelogram-type structure. Our Delta Haptic system was equipped with an electronic interface and software libraries, allowing the control to be conducted in the general ROS environment used in the framework of the STIFF-FLOP project. The communications interface between the Delta Haptic system and ROS was coded using a decimal format: XXX.X [mm], to achieve positions in the X, Y, Z space. Through these tests conducted between FCSD and PIAP, we could show that the connectivity between console and STIFF-FLOP arm prototype via the Internet works satisfactory. The test was conducted successfully and represents an important step in the development of STIFF-FLOP haptic control interface.

During the workshop carried out in Warsaw, we had the opportunity to integrate components of the control system. First, the preparation of all components was started by individual teams. FCSD successfully demonstrated the working of the Delta Haptic system, visualizing the motion of the user input in a 3D virtual environment. The next step was a preliminary test of the control console, taking into account the haptic feedback and evaluating the feedback strength. The test was carried involving a STIFF-FLOP manipulator prototype (Chapter 2), for improved actuation and force/torque sensing. Due to lack of properly working force sensors, testing of haptic force feedback had to be abandoned. In these experiments, the haptics were interfaced only with the ROS system, and the transmission of position from the haptics device to ROS was checked (Figure 16.15).

Additionally, a functional verification of the 2:1 scaled phantom model in frontal plane of the abdominal area (described in Chapter 17) for new STIFF-FLOP manipulator was carried out (Figure 16.16). This test provided a means to check every sensor placed on the sacrum below the urinary bladder and the colon (near the anus). Another three sensors were placed inside the urinary bladder and iliac vessels to measure the force acting on the wall of this body part.

16.4.3 Telemanipulation FCSD-KCL RobinHand F

During the project evaluation studies, the STIFF-FLOP arm was remotely controlled using the FCSD Delta. The STIFF-FLOP manipulator was placed above the up-scaled FCSD phantom model, allowing the robot tip to operate in the frontal plane of the abdominal area (Figure 16.17).

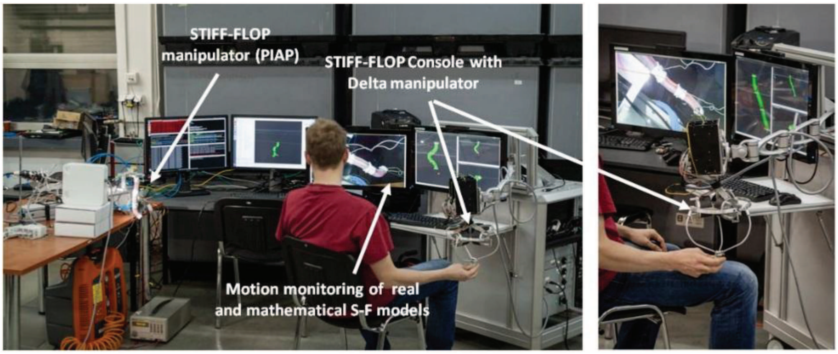

Figure 16.15 The STIFF-FLOP manipulator local control test.

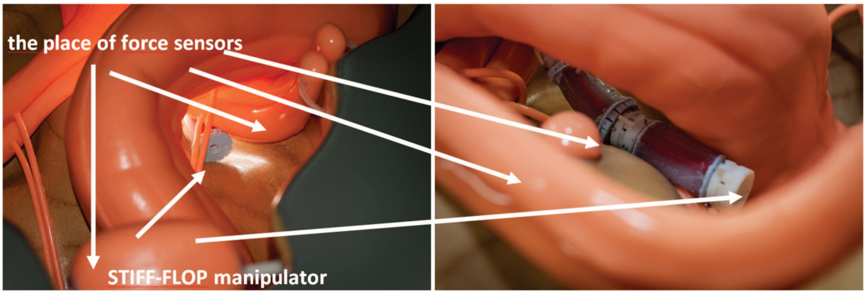

Figure 16.16 Functional verification of 2:1 scaled phantom models in the frontal plane (of abdominal area) for the new STIFF-FLOP manipulator (PIAP).

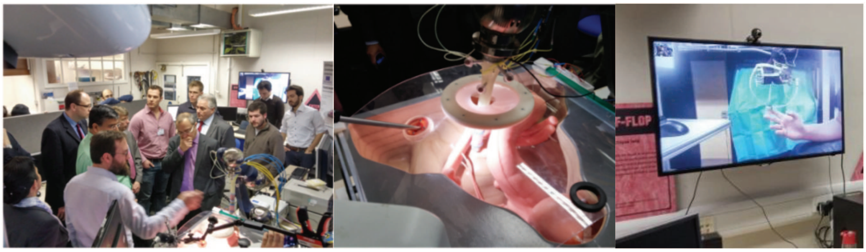

Figure 16.17 Telemanipulation evaluation studies at FCSD.

16.5 Integrating the Haptic Device RobinHand L with STIFF-FLOP Console

The final version of the *RobinHand L* actuator with seven DOF was adapted for STIFF-FLOP control console presented during the meeting in Torino (Figure 16.18). The first tests of the software integrating the actuator, the

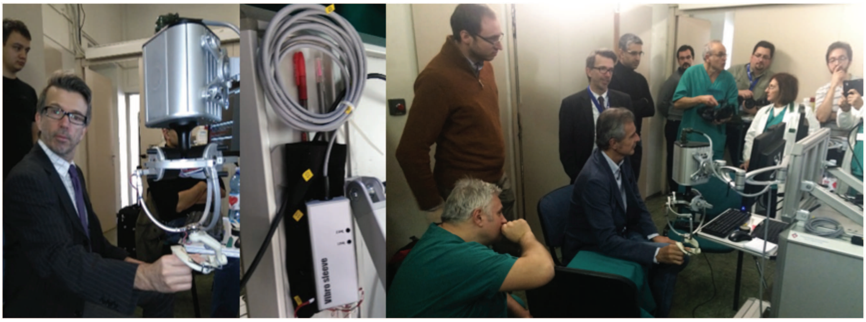

Figure 16.18 Presentation and tests of the integrated system.

console, and the vibrating sleeve were very promising. Another stage of development was presented during the meeting in London where the console was modified in order to make it more user friendly. Modifications were also made to the wiring, electronic components, and control software – to scale the forces impacting the operator. Additionally, the electronic part was equipped with cooling and ventilation systems to prevent it from overheating. The full integration took place in London where the project was successfully completed (Figure 16.19).

The actuator was also adapted for the brand-new version of the console where the mechanical part was separated from the electronic module. Haptic *RobinHand L* was modernized to meet the needs of INCITE project [15, 16]. Design and ergonomics were improved. The most recent Robin STIFF-FLOP console is shown in Figure 16.20.

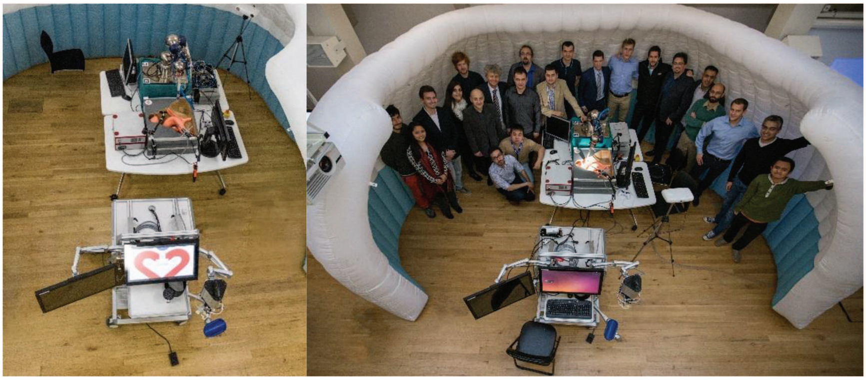

Figure 16.19 Final presentation of the STIFF-FLOP system.

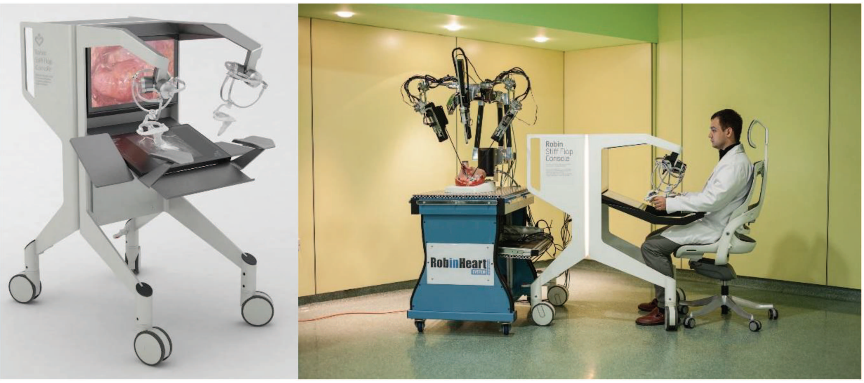

Figure 16.20 Robin STIFF-FLOP console: CAD model and integration with Robin Heart [16].

16.6 Conclusion

Biocybernetics Laboratory of the Heart Prosthesis Institute at the Cardiac Surgery Development Foundation is carrying out a Robin Heart medical robot project. Several models of the robot have been designed, made, and tested. The construction design and the control system, including the ergonomic console and actuator/motion controller, are continuously improved. In this regard, the greatest achievements of the Polish team include Robin Heart Shell 1 console, Robin Heart Shell 2 console, and Robin STIFF-FLOP console – with fully haptic motion actuator/motion controller and force feedback.

Currently, further testing of *RobinHand* haptic system is being conducted. All the results obtained so far indicate that it can meet customers' expectations and be put on the market. We hope that the knowledge and experience we have gained will allow us to provide surgeons with a comfortable workstation making remote operations safe and precise.

Acknowledgments

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