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Design of a Mechatronic Interface with Compliant Manipulator for Robot Assisted Echocardiography

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Abstract. A compliant manipulator with a compound soft actuator is proposed for robot-assisted echocardiography. The target application is devoted to the TOE echo (Trans-oesophageal echocardiography), which is conventionally performed by medical practitioners. The manual manipulation of the echocardiography probe shows significant risks such as human errors, exposure to ionizing radiation, and multitasking complexity. Automation of TOE provides advantages in terms of control, safety, and workload of the operator. This paper proposes a teleoperated robotic system assisting the physician to perform TOE, to be used in cardiac catheterization laboratories as well as hybrid operation theatres. A system containing a holder with master-slave Dynamixel servos and a manipulator with soft actuators has been developed. To alleviate the major lack of the previous designs in conducting the insertion tube, a robotic arm with a soft structure is proposed that has not hazards of conventional robot manipulators. The fundamental equations and relations for quasi-static control of the system are developed in this paper.

1. Introduction

Ultrasonic pulse echo, first employed by the Swedish physician Inge Edler (1911-2001) for producing echocardiographs, is routinely used in diagnostic tests and monitoring in cardiology. Trans-oesophageal echocardiography (TOE) is an ultrasound-based method to acquire cross-sectional images of the heart. TOE first emerged in the early 1980s [1-4]. A conventional TOE probe as used in the clinical context is shown in Figure (1.a) and (1.b). The probe handle contains two control knobs controlled manually by the sonographer during the TOE procedure. Turning the control knobs results in bending the distal end of the probe. The flexible shaft of the probe is inserted into the oesophagus of the patient. The ultrasound transducer is located at the tip. The proximal end of the handle connects the ultrasound machine with the probe and supplies the probe with electricity and enables the exchange of data. Image data acquired by the medical practitioner helps the cardiovascular interventionist to guide the catheter and evaluate the success of the operation. In a Ventricular Assist Device (VAD) implantation process, as an application example, TOE represents the established tool for measuring cardiac pump rate, to monitor and evaluate the function of the heart, the positioning of devices, as well as the assessment of patient-device interaction. Some standard views, which are utilized to perform a diagnosis of the heart, are obtained with varying probe tip pose. As the tip is turned or bent, the image will show the intersection of the imaging plane with the respective morphology. Comprehensive guidelines for performing a TOE examination are published as in [3] and [5].

A conventional TOE probe carries an ultrasound transducer mounted at the tip of an endoscope that is manually operated by a physician. The physician, during the operation, stands close to the patient body, which in turn causes many operation difficulties and risks for both the patients as well as the doctors. If the sonographer could work remotely, there would be less risk. For example, in a surgery room with the presence of many doctors, it would be desirable to keep the sonographer out of the room; and in Cath-lab, where the doctors are exposed to X-Ray, it will be healthier for the sonographer to keep distance from the X-Ray source. Medical robots [6], particularly flexible manipulators [7-8] or soft robots [9] with their reduced hazards due to malleability are good candidates to assist the sonographer. For this particular application, robotic solutions are investigated to assist surgical or echocardiography systems [5,10]. A robotized TOE system can employ the state of the art technologies in robot control and image processing technologies in order to obtain the image results optimally and automatically.

This paper presents the design and control of a robot for controlling the position and posture of the TOE probe. An alternative robotic solution was proposed to handle TOE procedure remotely. Based on a continuous robot model, and constant curvature assumption, a straightforward modelling method has been presented for manipulating the system. As the system is quasi-static, the modelling is targeted at the positioning without considering inertial effects and feedback control. A PC-based system was implemented using proper interfacing circuits transmitting the physician's instructions from the computer to the robotic slave system in order to display patient parameters and to monitor the status of the system. The automation system represents a module that is added to the traditional system and may be removed on demand. The proposed automation system shall optimize the procedure rather than replacing the medical practitioner operation.

a) TOE probe handle b) TOE probe tip

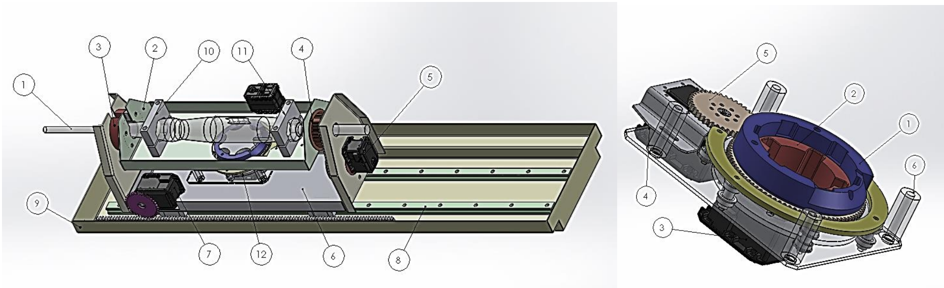
Figure 1. Conventional TOE probe

2. The proposed robotic solution

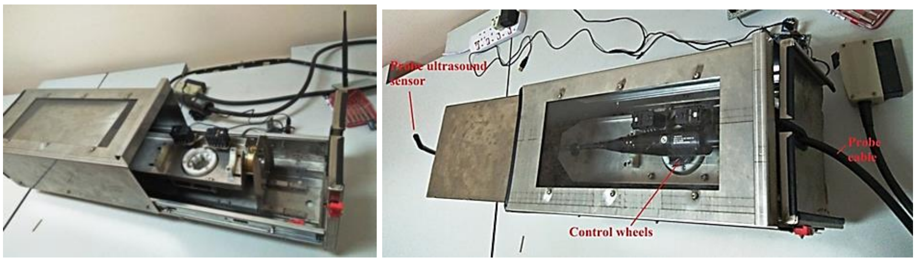
The proposed system consists of two main subsystems, one rigid and one flexible section. The first subsystem provides the main degrees of freedom (DOF) for manoeuvring the probe and is termed holder in this paper. It was made with conventional rigid parts and Dynamixel servos. As will be discussed later, in practice the rigid conventional systems suffer hazards and limitations. The second subsystem is a flexible arm developed for alleviating the limitations and disadvantages of the system.

2.1. Holder design

The holder system consists of master-slave system components controlled via a manual input device. The probe is inserted into the holder which is connected to the master system and corresponds to given commands which in turn results in posture variations in the probe tip. In practice, seven DOFs are required to operate a TOE procedure using controlled actuators. The DOFs include turning of the knobs, advance and rolling of the probe along its axis, pushing the electronic buttons, and the lock turning. Each DOF is manipulated by an actuator that has a built-in AVR microcontroller. The actuators are connected together with a serial bus, which is connected wirelessly to a PC as the main controller. The mechanical coupling between the actuators and the probe is provided by the holder mechanism, designed for this purpose. Figure (2) represents the holder design and the fabricated prototype. The main parts are described referencing numbers from 1 to 12 in Figure (2.a). Number 1 is assigned to the probe, which is fixed in the rotation tray, 2. Bearings, 3 and 4, provide the rotation with respect to the probe shaft axis. Thus, tray 2 is rotated using the bearings, a pulley mechanism at 4, and motor 5. A U-shaped frame, 6, provides linear motion using motor 7 and its rack-and-pinion gear. Slider 8 is to smooth the linear motion. The sliders as well as the rack gear are fixed to the base, 9. An enclosure with a transparent door will be connected to the base to cover all the parts. Two clamps, shown as 11 and 12, are used to fix the probe on the rotation tray, 2. Furthermore, the knob control mechanism, 12, is fixed to the rotation tray and actuate each knob separately. The knob control mechanism is shown separately in Figure (2.b). Two plastic parts are designed to grip the control knobs of the probe. As the probe is inserted, part 1 holds the bigger knob, and part 2 keeps the smaller knob. Actuator 3 is directly connected to 2. Actuator 4 drives part 2 with gear 5. The overall knob control assembly is fixed on the rotation tray with screw 6.



a) Design of the holder (without the cover) b) The knob control mechanism



c) The actual holder d)The holder with inserted probe

Figure 2. The holder mechanism and the fabricated prototype

Actual photographs of the holder system are given in Figures (2.c) and (2.d). The stainless-steel cover slides easily as in Figure (2.c), and the probe is mounted easily in the holder as in Figure (2.d). Originally, the design concept of the master-slave holder has been investigated by some researchers, and some prototypes have been developed. An example of a 3D printed design is presented in [10]. In this study, a mechanically robust system has been fabricated based on the concept and similar hardware and control system. In practice, however, the conceptual design has shown important incapability. As the system is based on rigid actuators and mechanisms, it can apply severe force on the patient body during moving the probe. In fact, the interaction force at the probe tip is not controllable. Another problem is that the tip can stop in the oesophagus during guiding and insertion of the probe, and the probe is jammed or bent. To alleviate this limitation, we propose an arm having compliance with respect to external force exertion at the end effector. A robotic arm, as in Figure (3), with soft actuators, as in Figure (4) and (5), is proposed to support the axial positioning and motion of the probe. Note that in the rigid manipulators with geared motors it is not easy to move the end effector with external force, and so, interaction force is high and dangerous. However, the proposed design provides an arm that can show compliance due to its structural bending. The design is described in the following subsection.

2.2. Design of the compliant arm

The proposed arm consists of a two-link arm, and a soft actuator. The links are connected with two pulleys at the joints, as in Figure (4.a), with crossed string belt that provides reverse rotation for the pulleys. With this simple trick, the gripper moves only in one direction, namely the approach direction. The actuator is developed using cylindrical McKibben muscles located at the sides of a prismatic malleable beam. The design principle is described as follow. Figure (4.b) represents a bending mechanism that consist of a beam with a rectangular cross-section considered at B_1B_2 line, and two soft muscles located laterally at A_1A_2, and C_1C_2. The centre points A_1 and C_1 are connected with string to B_1. Likewise, points A_2 and C_2 are connected to B_2. The lengths of A_1A_2, B_1B_2 and C_1C_2 are equal. When pressure is exerted to C_1C_2 muscle, it shows contraction and moves to a new straight posture, $C''_1C''_2$The contraction makes the malleable beam bends to $B'_1B'_2$ and the other muscle simply follows the bending (With a small amount of string clearance, the inactivated muscle will stay passive). The final design can be considered as three serially connected bending mechanisms with medial muscles for smooth bending as shown schematically in Figure (5).

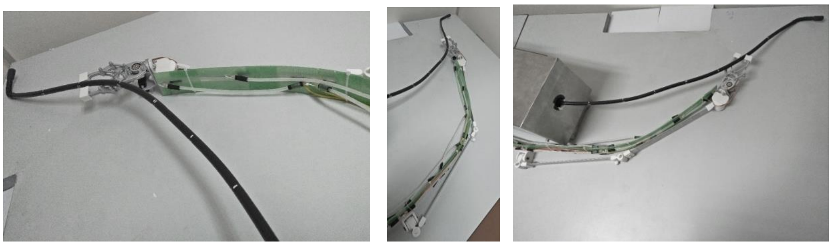
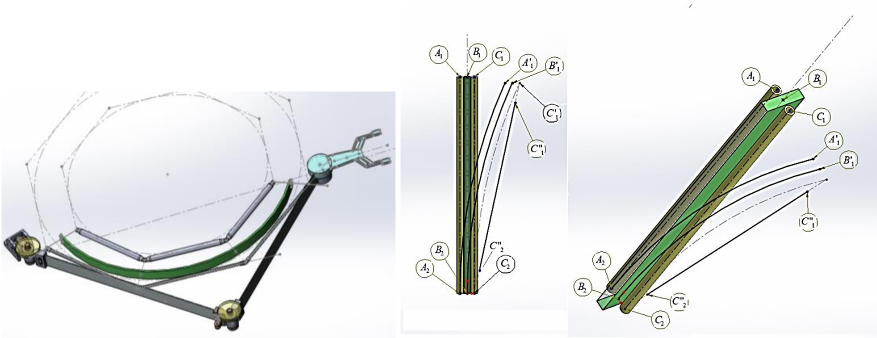


Figure 3. The flexible arm with soft actuators



a) Free body diagram of the arm, b) The bending sections of the soft actuator

Figure 4. Design of the arm

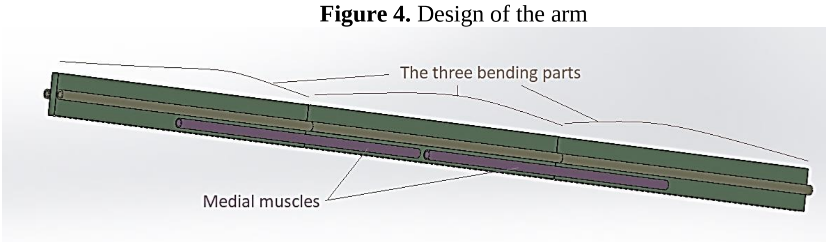


Figure 5. The overall soft actuator

2.3. Main kinematic equations

In quasi-static motion, the math effects and dynamics of the system is ignored. This supposition is reasonable because, in fact, the mass and inertia of the proposed arm is very low (0.2 Kg) and it will work in low speeds. Nevertheless, some kinematic equations are required for manoeuvring the system. These equations represent calibration relations that map the motion of the actuators to the motion of the probe. In this work, one pressure control valve is used for all five muscles at each side to achieve equal contraction ratio for the muscles. Let the contraction ratio of the McKibben muscle is defined as in (1)

$$\alpha = \frac{\bar{a}}{\hat{a}} \tag{1}$$

Where $\bar{a}$ is the actuated muscle length and $\hat{a}$ is the nominal length of the muscle. Supposing the malleable beam is a circular arc of amount 2θ belonging to a circle with radius r, simple geometric calculation results $\bar{a} = 2r\sin(\theta)$ and the arc length $\hat{a} = 2r\theta$. Therefore, the arc angle is obtained from solution of equation (2)

$$\sin(\theta)/\theta = \alpha \tag{2}$$

The solution can be achieved numerically and be shown graphically as in Figure (6). For $\alpha = 0.9$, which is practically the nominal value for the current actuators, the solution is obtained as

$\theta = 0.78 \quad rad$ or approximately 45°. This is corresponding to $2\theta = 90^o$ which means the malleable beam is forming a quarter of a circle in this situation.

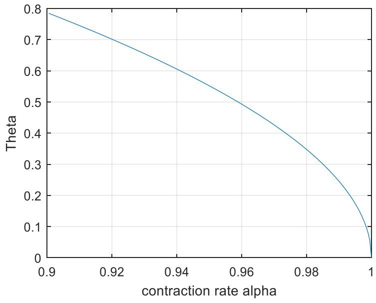


Figure 6. Arc angle *vs*. contraction rate

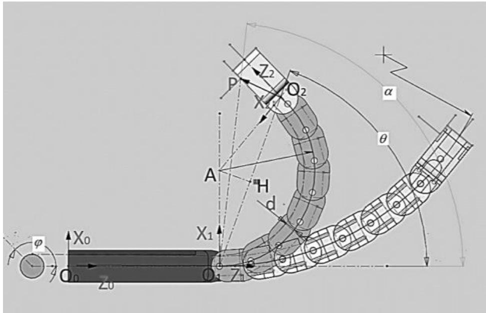


Figure 7. Model of probe under ante flex-retroflex

With differentiating and some arrangements we will have

$$\delta\theta = \frac{\theta}{\cos(\theta) - \alpha}\delta\alpha \tag{3}$$

Let the distance between the joints of the arm is represented by Z_0 (which represents the *advanced-withdrawn* of the probe, in the approach direction of the gripper). Then, we have

$$Z_0 = \frac{L\sin(3\theta)}{3\theta} \tag{4}$$

Where, $L = 3\hat{a}$, is the overall length of the actuator and is a constant value. From (4) we obtain

$$\delta Z_0 = \frac{L\cos(3\theta) - Z_0}{\theta}\delta\theta \tag{5}$$

Then, replacing (3) in (5) we obtain

$$dZ_0/dt = \frac{L\cos(3\theta) - Z_0}{\cos(\theta) - \alpha} d\alpha/dt \tag{6}$$

Now, some look-up tables can be produced with (2) to (6) to convert the soft actuator motion (given by α and $d\alpha/dt$) to the *advanced-withdrawn* of the probe. For the other DOFs of the probe, a method combining Homogeneous Transformation and constant curvature is proposed in the following equations.

Note that dissimilar to conventional robot manipulators, Echocardiography probes are not made with motorized rigid links and joints. However, they can be categorized in a class of manipulators know as continuum robots [8]. Formulation of the continuum robots is a complex procedure and active research area [9-12]. However, the assumption of constant curvature can considerably simplify the model. The method was first proposed for modelling an elephant trunk robot. The TOE probe tip consists of some serially connected rigid links. The interconnected links are driven using a string passed through the links. The string goes around a pulley and is driven manually by the rotation knobs. Figure (7) shows a free body diagram of the model and its frame assignments. The bending part is recognized by the O_1O_2 curve, which is a part of a circle with centre *A*, variable radius $r = AO_1$ and unchanging length $s = O_1O_2$. The sting is supposed to be at a distance of *d* from the curve. In a neutral position, the bending trunk is straight. When the string is twisted around the pulley, with a rotation amount of φ , the bending radius of the trunk is obtained as (7)

$$r = \frac{r_{pulley}}{2d}\varphi \tag{7}$$

where r_{pulley} represents the pulley radius. On the other hand, considering triangle AHX_1, the radius can be represented as (8)

$$r = \frac{s}{2\theta} \tag{8}$$

Note that $\theta = \angle HAO_1 = \angle HAO_2$, shows the angular motion of the tip respect to the neutral position of the prob. In this context, the kinematic equations of the model are derived. Only three coordinate frames are used. The first frame, frame 0, may be supposed fixed at any point of the oesophagus or at the location of the oral guide, with Z_0 being along the probe shaft. The probe shaft can be *turned* as well as *advanced-withdrawn* along Z_0. Frame 1 is located at O_1, the starting point of the bending part of the probe. For modelling simplicity O_0 is supposed close to O_1 such that O_0O_1 can be modelled as a rigid straight link. Frame 2 is located at the end point of the bending part. The tip or the ultrasound sensor centre, point P, is given as a constant vector respect to frame 2, given as $P_s^2 = [x_p^2, y_p^2, z_p^2]'$.

Homogeneous transformations include both rotation and translation of a frame in one matrix. Referring to Figure (7), simple geometric calculations show that frame 1 is projected (inside the X_1Z_1 plane) to frame 2 by a rotation of 2θ around Y_1, shown mathematically as $Roty(2\theta)$, and a translation of $\overrightarrow{O_1O_2} = [2.r.\sin^2(\theta), 0, 2.r.\sin(\theta).\cos(\theta)]'$. Then flex to right by angle θ_F around Z_1 describes the out-of-plane bending which is shown by rotation matrix $Rotz(\theta_F)$. Thus the homogeneous transformation transporting frame 1 to frame 2 is given as:

$$H_2^1 = \begin{bmatrix} Roty(2\theta)Rotz(\theta_F) & \overrightarrow{O_1O_2} \\ 0\ 0\ 0 & 1 \end{bmatrix} = \begin{bmatrix} c\text{os}(2\theta)\cos(\theta_F) & -c\text{os}(2\theta)\sin(\theta_F) & \sin(2\theta) & 2r\sin^2(\theta) \\ \sin(\theta_F) & \cos(\theta_F) & 0 & 0 \\ -\cos(\theta_F)\sin(2\theta) & \sin(\theta_F)\sin(2\theta) & \cos(2\theta) & \sin(2\theta) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9}$$

Similarly, the transformation from frame 0 to frame 1 is given as (10)

$$H_1^0 = \begin{bmatrix} Rotz(\psi) & \overrightarrow{O_0O_1} \\ 0\ 0\ 0 & 1 \end{bmatrix} = \begin{bmatrix} c\text{os}(\psi) & -\sin(\psi) & 0 & 0 \\ \cos(\psi) & \sin(\psi) & 0 & 0 \\ 0 & 0 & 1 & a_d \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{10}$$

Where the angle ψ is known as the turning angle and translation a_d is known as the advance motion. Now the transformation from frame 0 to frame 2 is obtained by matrix multiplication as follow

$$H_2^0 = H_1^0 H_2^1$$

The homogeneous transformation is sufficient to represent sensor position, given as point P with a constant vector $P_s^2 = [x_p^2, y_p^2, z_p^2]'$, in frame 0 as P_s^2

$$P_s^0 = H_2^0 P_s^2 \tag{11}$$

A mechanical model, namely tester, of the actuated part of the TOE probe is used instead of the actual TOE probe. This is because the TOE probes are protected due to their medical importance and expensive price. Figure (8) shows the structure of the tester representing the active part of the probe, *i.e.* the bending section of the tube made with a 1:1 scale. However, the inactive part is short because this part only guides the strings to the actuated part. The bending part consists of small links serially jointed together and driven by a string that goes through the links. The fabricated experimental setup is shown in Figure (8). A shaft encoder is used to measure the pulley angle which is adjusted manually using the pulley rotation handle. An IMU sensor is used to measure output angles. For measuring the sensor position a free tracking software was used as the IMU position output is noisy. The device was used to verify the kinematic model as summarized in Figure (9). Note that, instead of the second control knob, one can rotate the probe shaft to change the plane.

2.3.1. Manipulation of the holder

The TOE probe is put inside the robot which receives the instruction via a serial communication bus. Yet, the probe has its regular connection to its monitoring and control system using its cable. In fact, each *Dynamixel MX-64* servo actuator has its own micro controller, and all of the actuators are connected to a serial bus. Thus, a master-slave positioning of the servo can be easily realized as in [15]. The actuators have their local PID controllers which perform the feedback control task. The interaction between the robot and the probe is restricted to physical force/torque applied by the actuators. Interfacing of the actuators to a computer was realized using MATLAB. A GUI gets real-time instructions from the user, and the actuators are manipulated to desired positions with a predefined velocity.

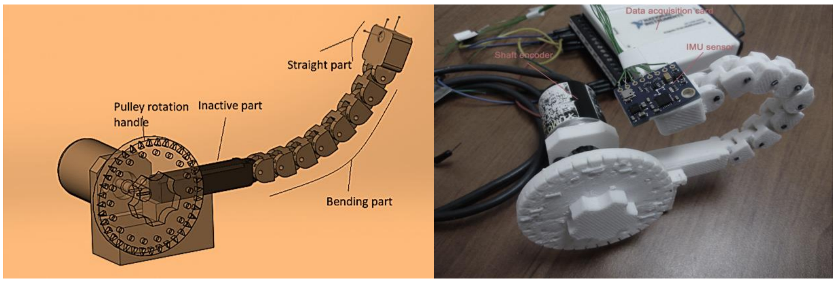


Figure 8. Structure design of a tester model and the experimental setup

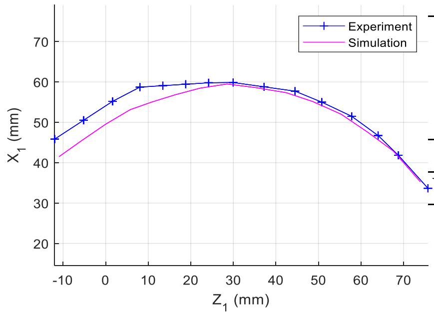


Figure 9. Tip trajectory

Table 1. Design parameters of the experimental setup.

	Pulley diameter	String Distance	Trunk length	Sensor position		
Parameter	D_0	d	s	x^2_p	y^2_p	z^2_p
Value[mm]	6.2	3.1	73.8	13.5	0	4.9

A stand-alone microcontroller-based wireless communication system based on radiofrequency (RF) 433MHz has been used for the system communication. In parallel with the GUI, a hardware manual control panel is used to send the desired position to the actuators. The physician can choose the respective module they want to work with. The system was equipped with a simple control panel for manual operation in case the computer fails. In the PC-based system, on the other side, the physician controls and monitors the system using a GUI. The GUI designed using MATLAB for real-time control of the machine. A program was developed to enable the operator to run all motors simultaneously. One slider is assigned for representing the position of each actuator. Each object calls a *callback* function when the program is executed. The *callback* function of the sliders executes a function as

movemotors(Position,ID);

where *Position* is the desired destination or angular position of the actuator shown by *ID*. The instruction used to run the motor is

calllib('dynamixel','dxl_write_word',ID,Position,Instruction);

The start button initializes the program by calling the required library and opening the port. Pushing the *start* button brings all the actuators to their assigned initial value as the reference position. Similarly, the *stop* button brings back all the motors to the initial position and closes the library. The torque applied by the motors of the robot should not exceed the maximum tolerable limit. In the manual operation the doctor feels the resistant torque on their hand and has control on it. Likewise, the robot should mimic the controlled torque. For this reason, a torque limit is used for the system.

3. Conclusion

The development of a novel mechatronic system as a medical robot performing as an interface between the human operator and the ultrasound imaging probe was introduced. The system is meant to enable the sonographer to operate the probe remotely in the scale of meters far from the patient undergoing the process. The philosophy behind the design is to preserve the probe intact and provide a machine that manipulates the probe with master-slave functionality. It was discussed that previous designs had major incapability in conducting the insertion tube inside the oesophagus. We proposed a flexible arm with compound soft actuator that unlike electrical servos is not stiff with respect to external forces at the tip. The fundamental equations and relations for quasi-static master-slave control of the system were derived. Employment of the soft actuators provided a safe interface for interaction with human, either the patient or the medical team present in the semi-intrusive practice. The prototype convinced that the robotic arm with the specific design has not hazards of conventional robot manipulators. The experiments convinced us that the quasi-static model is adequate for manipulation of the system. It is concluded that the proposed solution proposes a bridge towards safe and ergonomic cardiac sonography. The next stage of the medical device development would be validation and clinical trials.

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