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Design, Prototyping and Evaluation of a New Robotic Mechanism for Ultrasound Imaging

Alireza Abbasimoshaii[a], *Farshid Najafi*[b,*]

[a] *Department of Mechanical Engineering, Tarbiat Modares University, Tehran, Iran*
[b] *Department of Mechanical Engineering, University of Tehran, Tehran, Iran*

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ABSTRACT

This paper presents a new robotic mechanism for ultrasound imaging. The device is placed on a patient's body by an operator, and an ultrasound expert controls the motions of the device to obtain ultrasound images. The paper focuses on the robotic mechanism that performs ultrasound imaging. The design of the mechanism is based on two approaches to produce center of motion for an ultrasound probe. This center of motion which is located on the tip of the probe helps to create clear ultrasound images. Detailed designs, kinematic relationships, prototyping and ultrasound imaging tests are presented. A novel cabling mechanism is developed to create the center of motion required for ultrasound imaging. The mechanism provides all four necessary motions for ultrasound imaging by using two actuators which significantly reduces the weight of the device to make it suitable for portable ultrasound applications. The device has been successfully used for ultrasound imaging of kidney, gallbladder, liver, ovary and uterus of volunteer patients.

1. Introduction

This work was originated by the desire that uniform health services should be provided to all citizens. Remote-diagnosis is an approach to address some of the problems associated with the distance between patients and medical experts. Skilled personnel are not available at every location. Small clinics and hospitals, battlefields, or remote locations such as space stations typically lack trained personnel [1]. Ultrasound imaging is safe and can be used for diagnosis of many health issues [2]. Ultrasound examination services are not usually available in rural or isolated areas, often results in inconvenience and/or insufficient use of resources.

The objective of this paper is to develop a robotic mechanism that can be used in a robotic system suitable for ultrasound examinations. Such a system enables medical experts to perform ultrasound diagnosis on patients located in remote or isolated areas [2].

In this paper, conceptual and embodiment design, kinematic relationships, prototyping, and evaluation of the robotic mechanism are presented. The device provides all four necessary motions for performing ultrasound examinations by using only two electrical actuators. It has a center of motion to facilitate free-hand ultrasound scanning. A novel cabling mechanism is used to create the center of motion for the ultrasound probe.

Cable mechanisms are generally much lighter as compared to linkage or gear mechanisms presented before [3]. If the contact point between the probe and the patient’s body is lost, the ultrasound images will be disrupted. The mechanism that provides the center of motion is mounted on a proper compression spring platform. The spring platform inherently maintains the center of motion of the probe on the patient’s body. In order to be easily handled by an operator, the device should be portable [4]. Less actuators and light mechanisms makes the present device a portable one, as it can be moved from one to another location to provide ultrasound diagnostic services.

The rest of the paper is organized as follow. In the beginning, the necessary movements for free-hand ultrasound examinations and relevant literature review are explained. Section 2 outlines general design requirements and objectives. Section 3 describes the conceptual design of the mechanism. In sections 4 and 5, the embodiment design of the robotic mechanism is presented. In section 6, kinematic relationships are derived. Section 7 explains the prototyped mechanism and performance evaluation results. Section 8 outlines the contributions of the present work.

1.1. Free-hand ultrasound examination

In ultrasound examination, very high frequency sound waves are sent to the areas of interest and the returning signals are registered. In free-hand ultrasound examination, the expert manipulates the ultrasound probe on the patient’s body, and

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[*] Corresponding author: Tel.: +0919-815-6491; fax: +021-61119961; e-mail: farshid_najafi@ut.ac.ir

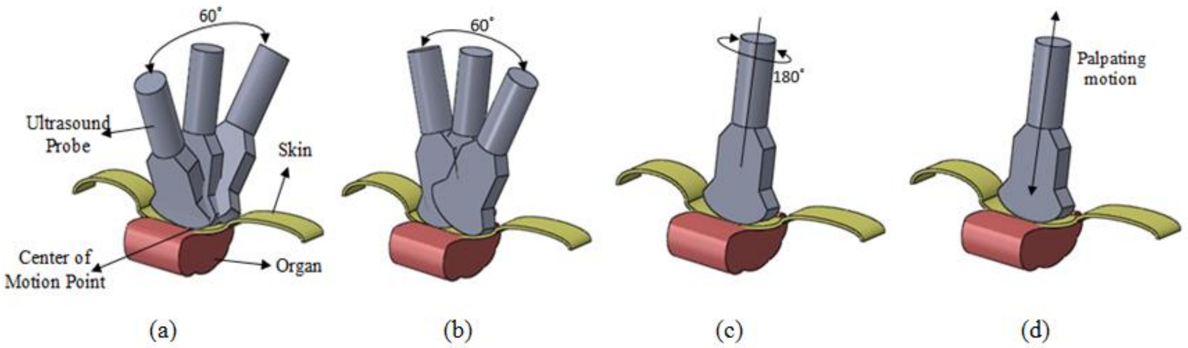

Figure 1 Free-hand ultrasound examination, a) Pitch scanning b) Yaw scanning c) Rotational scanning d) Palpating motion

based on the recorded images, he/she makes the diagnosis. The manipulation schemes are shown in Figure 1.

The ultrasound probe is manipulated about a point on the patient’s body called center of motion. When the patient's body moves up and down, the robot should maintain the center of motion on the patient’s body by compensating the abdominal motion. Therefore, deploying a proper mechanism to inherently maintain the contact is one of the goals of the present paper. The suitable workspaces for different scanning schemes are shown in Figure 1 [5].

1.2. Relevant literature review

Sublett et al. [6], for the first time, introduced the concept of the remote ultrasound imaging. The authors presented the implementation of a digital image capture and distribution system to support remote ultrasound examinations. A serial[1] six degree of freedom, DOF, articulated robotic arm for moving an ultrasound probe on the patient’s body was developed by Degoulange et al. [7]. The end-effector of a serial manipulator has force interactions with the environment while performing a position/force control task [8]. To reduce the joint fatigue of the ultrasound technicians, Salcudean et al. [9] developed an ultrasound robot. The authors used a pantograph to generate a conical motion about a remote center-of-motion (RCM) point on the patient’s body. A robot for tele-echography resting on the patient’s body during examinations was designed and constructed by Masuda et al. [10]. Mitsuishi et al. [11] and Koizumi et al. [12] created a robotic system for ultrasound examinations consisting of circular guides. The device consists of three degrees of freedom, and has a serial configuration with floating actuators. The ultrasound probe is manipulated about the center of a gear mechanism fixed to the circular guides. One of the challenging problems in developing a dexterous and a versatile robot is to design a statically balanced robot having high number of degrees of freedom [13]. A hybrid mechanism embracing the patient's body was used by Vilchis et al. [14] to manipulate an ultrasound probe. Delgorge et al. [5] described the European OTELO project which included a 4-DOF robotic arm. Lessard et al. [15] used a hybrid robotic arm consisting of a 5-bar mechanism to move the probe in a desired plane for three dimensional ultrasound imaging. Vilchis et al. [16] designed and constructed a 4-DOF robotic arm, TERMI, for ultrasound examinations, similar to the ultrasound robots developed by Mitsuishi et al. [11] and Koizumi et al. [12]. In this work, the authors used pinion gears in a serial configuration to move circular sliders. A 4-DOF robotic wrist with kinematically decoupled movements based on an unsymmetrical parallel mechanism for remote ultrasound examinations was designed and constructed by Najafi and Sepehri [17]. Nakadate et al. [18] designed a serial 3-DOF robotic arm to assist ultrasound technicians during examinations. To hold the probe at a desired orientation on the patient’s body, the authors used two passive ball joints.

Ito et al. [19] designed a 4-DOF robotic system which is placed on the patient's abdomen for ultrasound examinations. Two springs are used to maintain the contact between the probe and the patient’s body. A 6-DoF parallel robot for abdominal ultrasound examinations is used by Monfaredi et al. [20]. This robot had a force feedback system to control the movements. Krupa et al. [21] used a haptic probe that remotely controlled a robotic device. A robotic device with 6 DOFs was designed by Masuda et al. [22] which moves the probe in three dimensions, and measures the contact force between the ultrasound probe and the patient’s body, utilizing an unsymmetrical parallel mechanism with three legs. The ultrasound expert manipulates the probe through the operator’s hand-grip, while position and orientation of the probe are measured by position sensors. Loschak et al. [23] designed a 4-DOF robot for positioning ultrasound image catheters. Ren et al. [24] designed a soft robot which is able to be attached to the patient’s body. This robot is able to move in three directions and has four parallel soft actuators. Lindenroth et al. [25] designed a soft robot for robot-guided ultrasound interventions. This robot has a parallel mechanism and uses compliant linear actuators integrated in the parallel mechanism. A 6-DOF robot is developed by Guan et al. [26] which has a mechanical arm that moves the ultrasound probe in different directions.

2. General Design Requirements

A detailed review of the above mentioned robotic devices is presented by Abbasi and Najafi [2] who presented new guidelines for the improved design of the robotic mechanisms for ultrasound examinations. These criteria are implemented in the design of the present mechanism, and are listed below.

1. Reducing the number of actuators is a significant improvement, due to reduction of cost and inertia. Pitch, yaw, and rotational scanning schemes need three actuators. Vilchis et al. [14] and Ito et al. [19] generated these three motions by using only two actuators which seems to be a significant improvement.

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[1] A robot is said to be a serial one if its kinematic structure takes the form of an open-loop chain, a parallel manipulator if it is made up of a closed-loop chain, and a hybrid manipulator if it consists of both open and closed-loop chains.

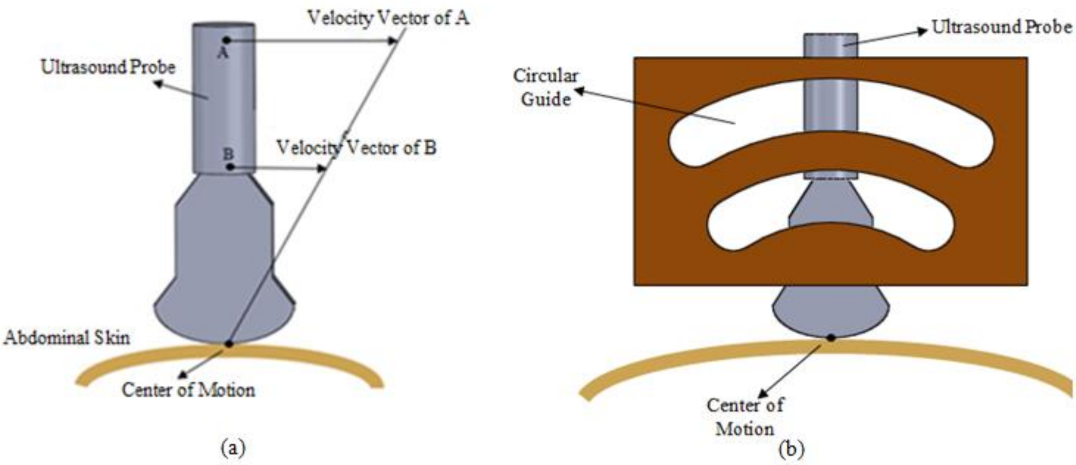

Figure 2 a) Conceptual Design I b) Conceptual Design II

2. The contact between the ultrasound probe and the patient’s body should be maintained in order to achieve a meaningful ultrasound image. Compression springs proposed by Ito et al. [19] reduce the number of actuators which simplifies the mechanical design.

3. Adaptable location of the center-of-motion can be achieved by using cable and spring mechanisms. This causes the contact point between the probe and the patient's body to be the center of motion.

4. The inertia of moving elements should be kept low to reduce the contact forces between the patient’s body and the mechanism by using light power trains such as belts and cable.

3. Conceptual Designs

The first concept is developed based on the fact that, if two parallel velocity vectors of points A and B of the ultrasound probe are known, the intersection of line AB, and the line connecting the velocity vector's end-points is the center of motion (Figure 2 a). If the location of this velocity vectors are properly selected such that the intersection point coincides with the tip of the probe, then, that point is the center of motion. In this paper, velocity vectors of points A and B are created by a new cable mechanism which will be described in detail in embodiment design I in the next section.

The second concept is developed based on circular sliders, (Figure 2b). If the probe is properly guided by one or two circular guides and is pushed to left/ right sides by a cable mechanism, the probe will be rotated about the center of the circular guides which is selected to be the tip of the probe.

4. Embodiment Design I

Figure 3 shows the general view of the proposed robotic mechanism. The operator holds the hand-grip bars to create a fixed base for the moving parts of the mechanism. The hand-grip bars are rigidly connected to the supporting plate which together generates the upper structure of the device. DC motor 1 is fixed to the upper structure. The lower structure consists of rigidly connected horizontal and vertical bars, and contains the ultrasound probe.

DC motor 1 rotates the moving plate. The moving and supporting plates are jointed together by a bearing (not shown). The moving plate and the lower structure are fixed together by the connecting rods. DC motor 1 rotates the moving plate and the ultrasound probe about the Z axis. The moving plate, the lower structure and the ultrasound probe are in YZ plane that can be rotated by motor 1 about Z axis to generate the scanning motion shown in Figure 1 c.

Encoder 1 measures the orientation of the probe. DC motor 2 moves the ultrasound probe through the main cable drive to generate the pitch/yaw scanning motions of the ultrasound probe about the center of motion (Figure 1a and 1b).

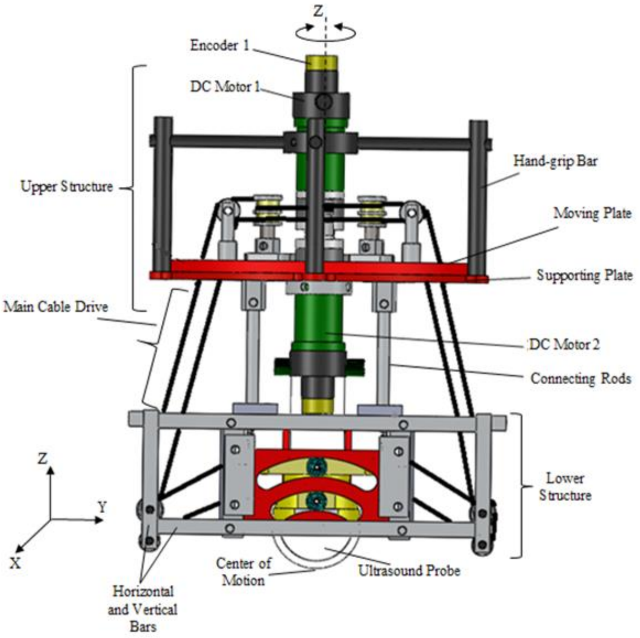

Figure 3 General view of robotic mechanism

The power train for achieving these scanning motions consists of DC motor 2, gear box 2, main cable drive, cable reducer, cables A, B and finally the ultrasound probe container (Figure 4). The main cable drive transmits the rotary motion of gear box 2 through the driver and guiding pulleys to the upper stepped pulleys located on the right and left sides of the device. The main cable is wrapped around the driver and upper stepped pulleys to

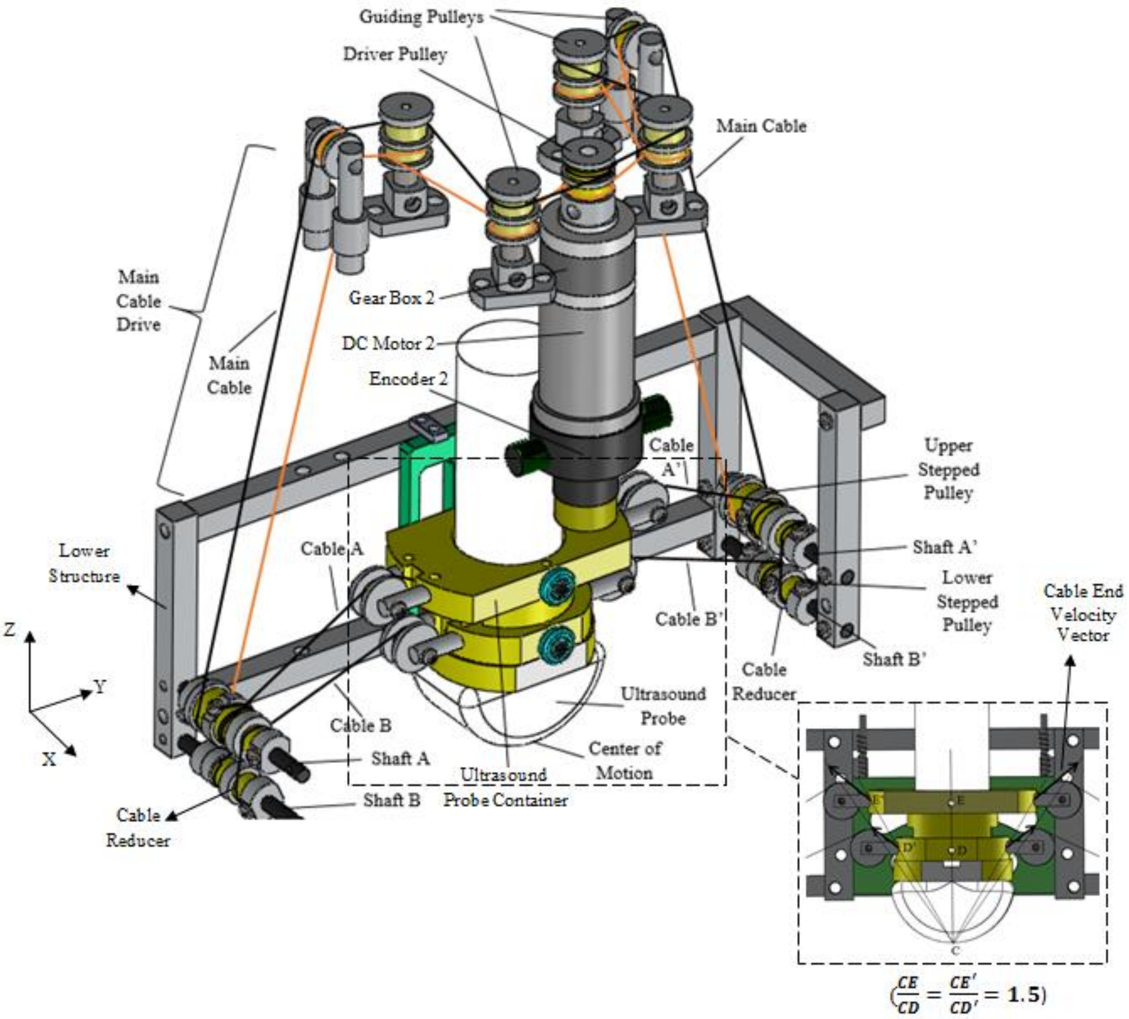

Figure 4 Embodiment design I

prevent slippage. The guiding pulleys freely rotate about their corresponding axes.

The rotary motions of the upper stepped pulleys are transmitted to the lower ones by the cable reducers. The reduction ratio is selected to be 0.5 in the present design. The lower stepped pulleys freely rotate about shafts B and B'. One end of cables A and A' are fixed to the sides of the probe container, where the other ends are wrapped around the middle part of the upper stepped pulleys. Similarly, one end of cables B and B' are fixed to the lower sides of the probe container, and the other end is wrapped around the middle part of the lower stepped pulley. Due to the cable reducers, the linear velocity of cable A is twice the velocity of cable B.

The two ends of cables A and B are kept parallel at their connections to the probe container. Due to the conceptual design presented in the previous section, the linear velocities of cables A and B causes the probe containers to rotate about the center of motion (Figure 4 closed-up view). Cables A, B and A', B' functions are opposite. It means that, when cables A and B are actuated, they are wrapped around their corresponding stepped pulleys, while cables A' and B' are unwrapped from their corresponding stepped pulleys.

When the ultrasound probe is in YZ plane, DC motor 2 can create the yaw scanning motion of the probe similar to one shown in Figure 1b. DC motor 1 can rotate the lower structure, and bring the ultrasound probe in XZ plane. In this configuration, DC motor 2 can generate the pitch scanning motion (Figure 1a). Encoder 2 measures the orientation of the probe in pitch and yaw scanning motions.

5. Embodiment Design II

This section presents the second embodiment design which creates the pitch and yaw scanning motions of the probe. Its power train consists of DC motor 2, gear box 2, main cable drive, cables A, A' and finally the ultrasound probe container which is restricted to move in circular slots (Figure 5). The main cable drive transmits the rotary motion of the driver pulley to the upper stepped pulley which in turn pulls cable A and the probe container to the left. The probe container is restricted to move in circular slot to provide the yaw scanning motion of the probe about the center of motion. The probe is fixed inside the probe container in a way that the tip of the probe is always located on the center of the circular slots (center of motion).

The plane of the circular slots is restricted to move in vertical direction by the vertical guides. The two compression springs press the probe container and the ultrasound probe on the patient's body to maintain the contact during ultrasound examination. Similar to embodiment design I, combinatory motions of DC motors 1 and 2 can generate the pitch scanning

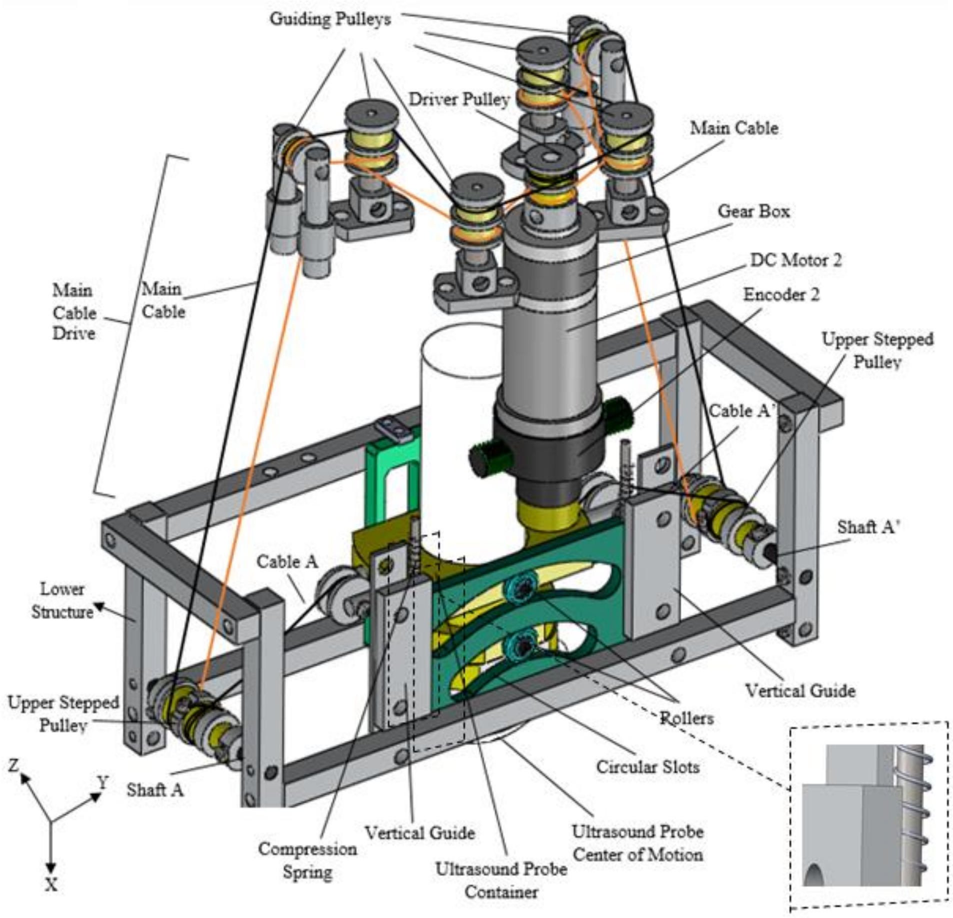

Figure 5 Embodiment design II

scheme (Figure 1a).

In this design, the circular slots that contains the probe seats on the compression springs. Therefore, when an operator places the robot on the patient's body, due to the contact force between the probe and the body, springs and the patient's body are compressed. This causes the tip of the probe to adjust its position with respect to the patient's body. This feature creates and maintains the contact point (center of motion) between the tip of the probe and the soft body. In the present design, the average contact force between the probe and patient's body is measured as much as 2 N. The stiffness coefficient of the springs and their strokes are selected to be as 4 N/mm, and 8 mm respectively.

6. Kinematic Analysis

In this section, the equations describing the relationship between the orientation of the ultrasound probe and motor rotation angles are derived. For inverse kinematic, the ultrasound probe is placed at angle θ in Figure 6, and motor rotations θ_m1 and θ_m2 which bring the probe to such orientation is calculated.

Motor 2 is connected to the upper stepped pulley by the main cable. Cable A' is wrapped around the upper stepped pulley, and the other end of the cable is fixed to the ultrasound probe container. The location of the contact point of the cable A' and the pulley is marked as F in Figure 6. The initial and final length of cable A', T1 and T2, to orient the probe as much as θ , are given by the following equations:

$$T_1 = ((X_1 - X_3)^2 + (Y_1 - Y_3)^2)^{(1/2)} \quad (1)$$

$$T_2 = ((X_2 - X_3)^2 + (Y_2 - Y_3)^2)^{(1/2)} \quad (2)$$

Where X_1=L_2, Y_1=L_1 and X_2, Y_2 are the initial and final location of point F, respectively. With reference to Figure 6, X_2 and Y_2 are calculated as follow.

$$X_2 = -L_1 sin\theta + L_2 \cos\theta - R_2 \sin\theta \quad (3)$$

$$Y_2 = L_1 cos\theta + L_2 \sin\theta + R_2 \cos\theta \quad (4)$$

L_1, L_2 and R_2 are fixed geometrical parameters. X_3, Y_3 is the location of the center of the upper stepped pulley. Motor rotation θ_{m2} is calculated as follow.

$$\theta_{m2} = (T_1 - T_2)/R_3 \quad (5)$$

Where R_3 is the radius of the upper stepped pulley, Motor 1 rotates the probe about its axis. For this rotation, θ_{m1} is equal to the rotation of the probe. All scanning schemes shown in Figure 1 can be achieved by combinatory motions of θ_{m1} and θ_{m2}. This leads to a conical workspace of the probe where the vertex angle of the cone is 60°.

7. Prototype Device and Experimental Evaluations

Figure 7 shows the prototype of the robotic mechanism. The robotic mechanism provides all four scanning schemes for ultrasound imaging by using only two DC motors (Figure 8).

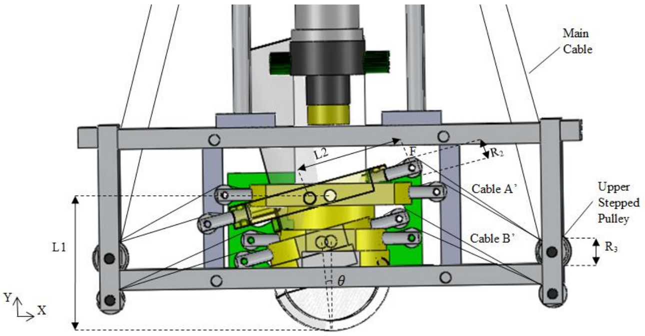

Figure 6 Geometry of probe movement

A new cable mechanism is developed to generate the center of motion for the ultrasound probe. The ultrasound probe is mounted on a spring platform to maintain the contact between the probe and the patient's body. The moving elements of this mechanism are made of aluminum and Plexiglas. The weight of the mechanism is about 1.5 kg, and its footprint and height are 254 × 81 and 300 mm, respectively. A cone with 60° as vertex angle is the nominal workspace needed for ultrasound examinations [17]. The device can be handled from one place to another one by an operator to provide ultrasound diagnosis services. Figure 8 shows the pitch, yaw, and spinning schemes of the ultrasound probe and their corresponding motions on the robotic mechanism.

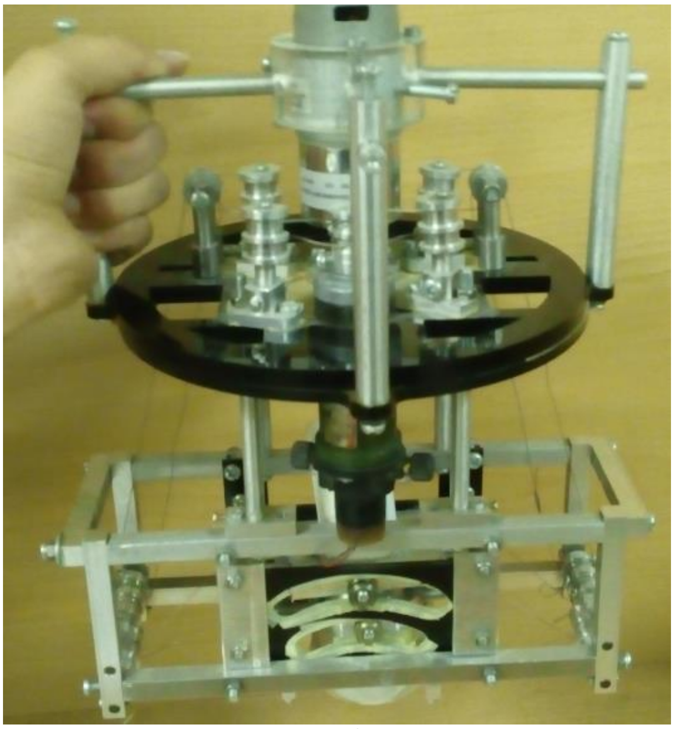

Figure 7 Prototype of robotic mechanism

In order to check if the center of motion remains fixed during the ultrasound scanning motions, an experimental setup is prepared. According to Figure 9, the mechanism is placed on a stand, and a laser pointer and a laser receiver sensor are placed on both sides of the mechanism. The location of the pointer and the sensor is adjusted in a way that the laser beam is tangent with the tip of the probe.

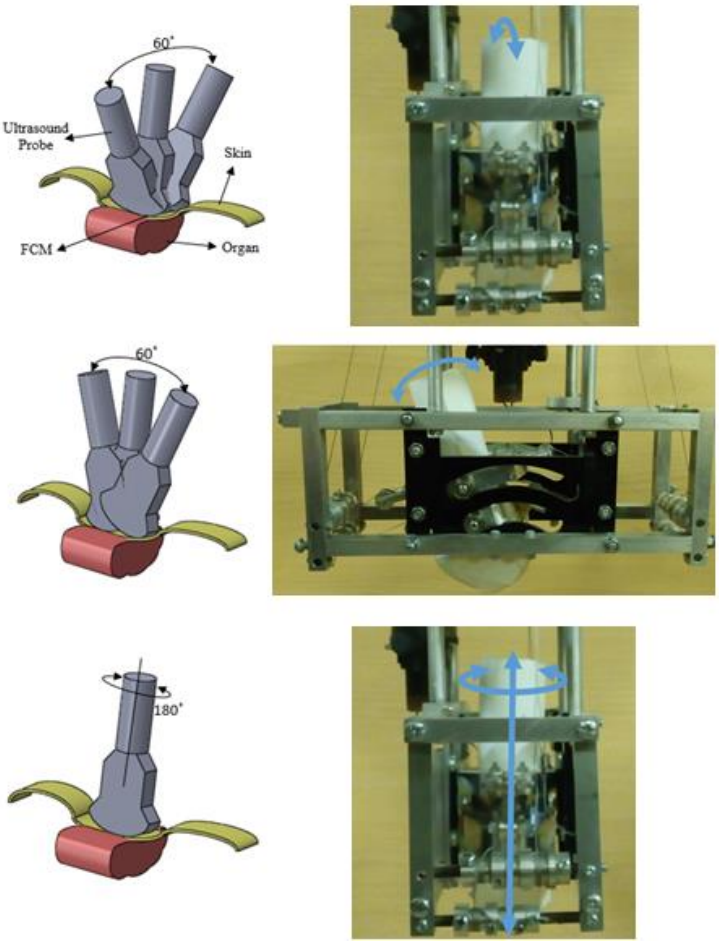

Figure 8 Ultrasound scanning schemes and corresponding motions of probe

When the laser beam is received by the sensor, an output voltage equal to 4.5 V is generated. When the probe is moved according to the standard scanning motions, the output voltage of the sensor is recorded and shown in Figure 10. The output voltage is non-zero which shows that the connection between the laser beam and the receiver maintained during the test. The small variations of the voltage are due to the movement of the whole mechanism and the fluctuations of the power supply voltage.

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According to embodiment design II described in section 6, the center of motion is always located on the tip of the probe, and the compression springs maintain the contact between the probe and the patient's body during ultrasound examinations. In order to check, if the contact between the probe and patient's body is maintained, a force sensor (Honeywell FS03) is attached to the tip of the probe when the whole mechanism is located on the patient's body, Figure 11. The output voltage of the force sensor is recorded during the breathing cycles of the patient, as shown in Figure 12. The results show that the contact between the tip of the probe and the patient's body is maintained by the compression springs with an average contact force equal to 2 N.

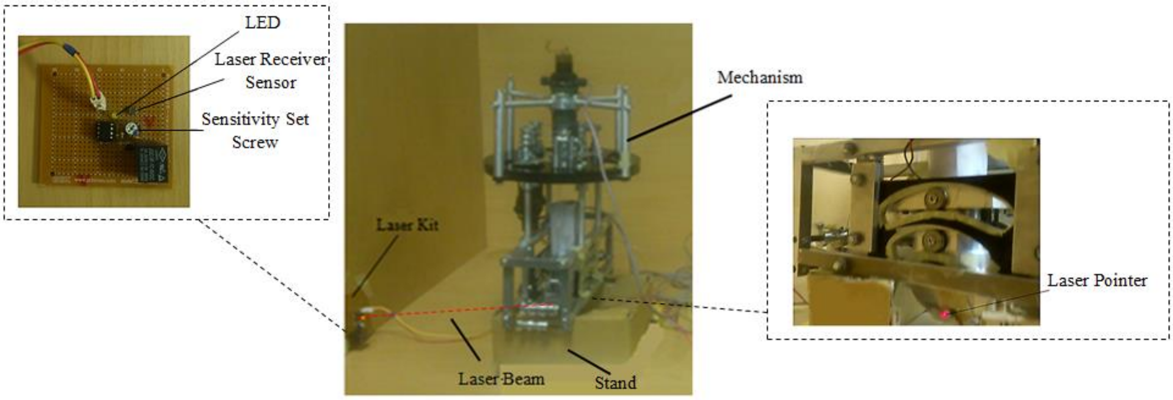


Figure 9 Experimental setup to check the location of center of motion

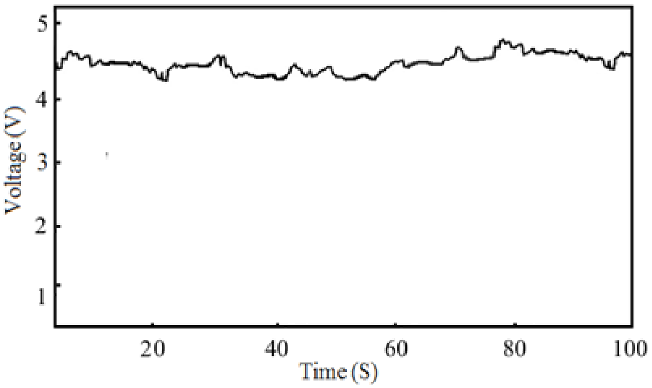


Figure 10 Output voltage of laser sensor

Finally, the device is placed on a proper location on volunteer's abdomen (Figure 13 (a)). The proper location is advised by an ultrasound expert. Ten ultrasound experts controlled the motions of the probe to capture ultrasound images from volunteers in Firouzgar hospital in Tehran. The experts were able to easily obtain the required ultrasound images of kidney (Figure 13 (b)). To evaluate the performance of the present device, images of ovary and uterus were obtained (Figure 14).

Figure 15 (a) shows an ultrasound image obtained by the present device from a volunteer's gallbladder. The expert was able to locate the gallstone seen as an echogenic mass with acoustic shadow behind it. The ultrasound image shown in Figure 15 (b) is taken from a volunteer's liver. The target lesion, hypoechoic lesion with echogenic center can be clearly seen as a sign of liver metastasis.

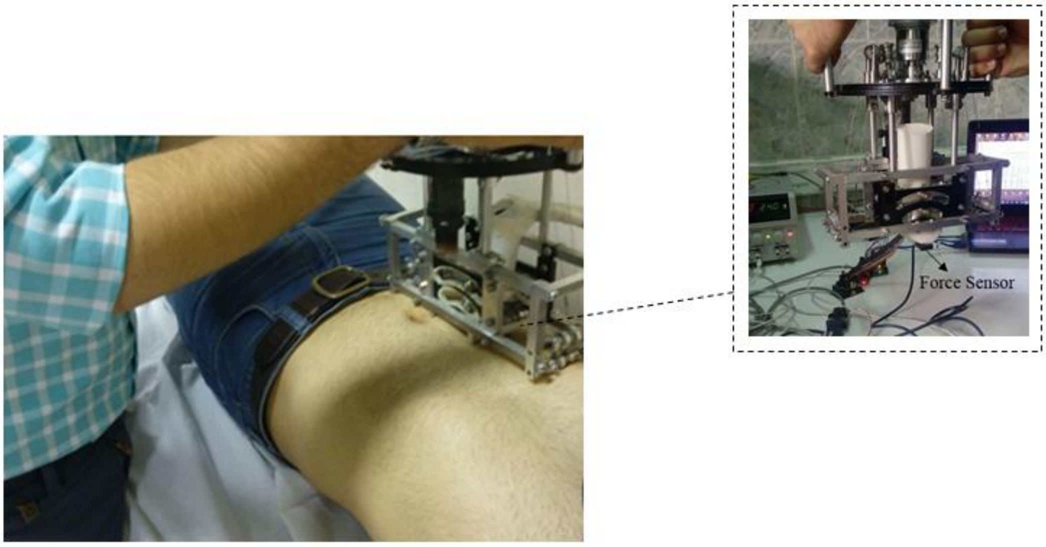


Figure 11 Experimental evaluation of maintaining contact between probe and patient's body

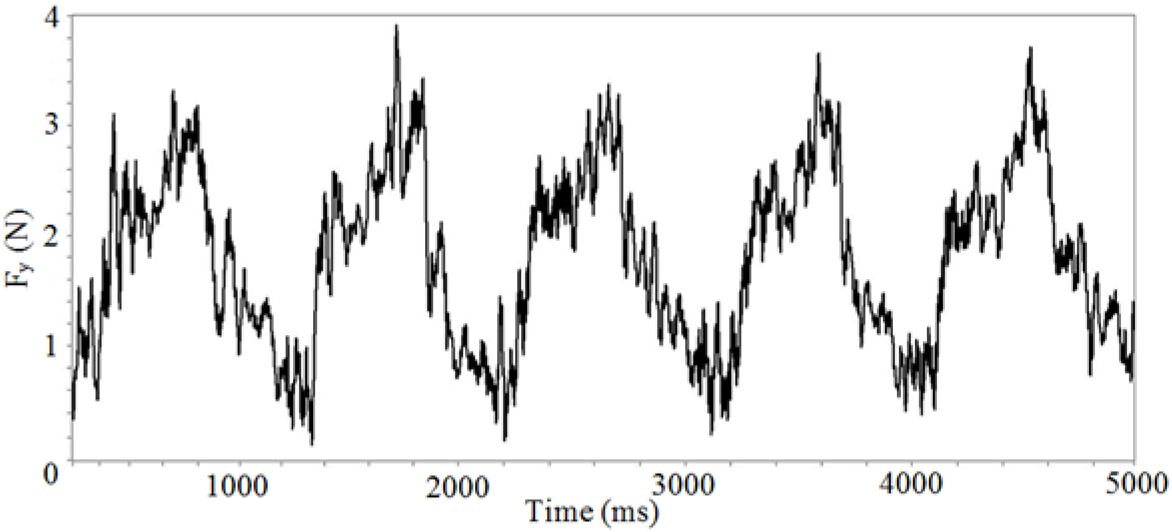
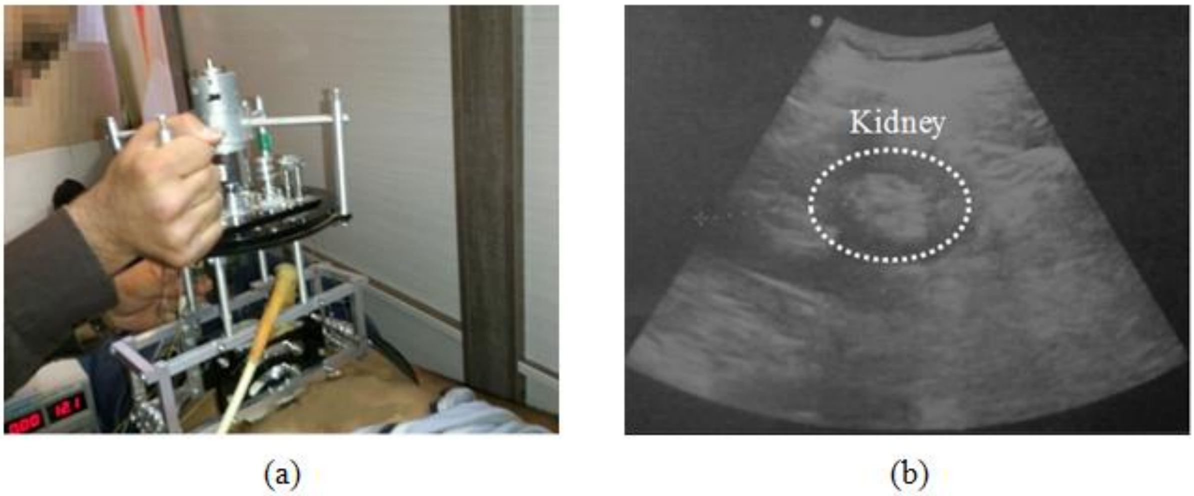
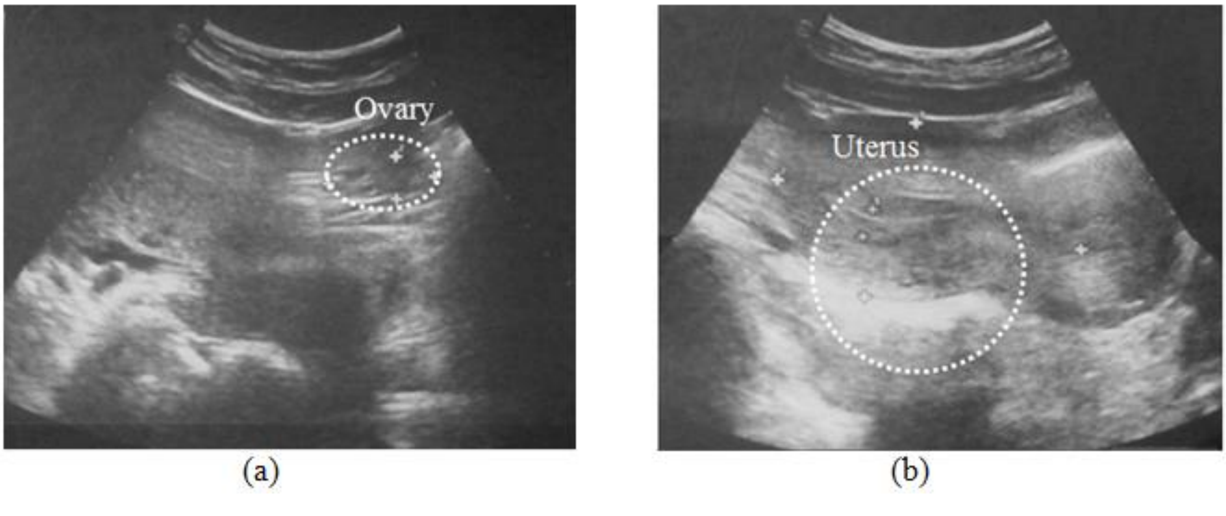


Figure 12 Contact force between probe and patient's body due to respiratory motions



(a) (b)

Figure 13 a) Ultrasound imaging b) Ultrasound image of kidney



(a) (b)

Figure 14 Ultrasound imaging, a) ovary b) uterus

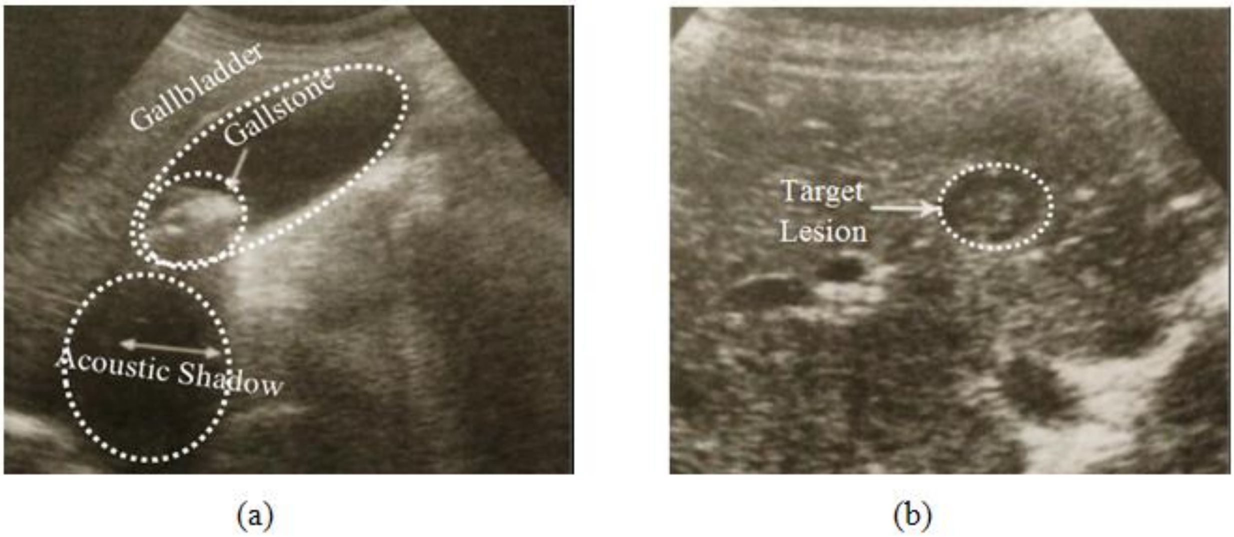


Figure 15 Ultrasound imaging performed on volunteers, a) gallbladder and gallstone b) patient's liver metastasis

8. Conclusion

A new robotic mechanism for ultrasound imaging has been developed. It has been deployed on volunteers to show its functionality. The device has a set of specifications which makes it unique among the previously reported robotic mechanisms for ultrasound imaging. A novel cabling mechanism is developed to generate the center-of-motion point of the probe to facilitate free-hand ultrasound imaging. All four necessary motions of the probe are achieved by only two electric actuators, which can lead to a light and cost-effective device for portable applications. Experimental evaluations of the robotic mechanism on volunteers show the applicability of the mechanism for ultrasound imaging diagnosis.

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