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Optimizing Reachability and Wrench Estimation in Robotic Ultrasound via Probe Holder Geometry

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Abstract: In robotic ultrasound the probe is attached to the robot's end effector using custom-developed probe holders. To enable successful and safe scans, high reachability of the target poses as well as precise probe contact wrench control are crucial. This study evaluates how different probe holder geometries influence the reachability as well as the accuracy of the internal wrench estimation model of the KUKA LBR iiwa 14 R820 performing US scans. It could be demonstrated that a probe, which is attached to the end effector with a small offset and 90° rotation increased the mean reachability by 16%. Moreover, mean Euclidian force estimation errors were reduced by 22% and mean Euclidian moment errors by 35%, compared to a typical tool geometry of a straight end effector extension. Thus, the results show a promising approach to improve the accuracy of the robot wrench estimation in medical applications.

Keywords: robotic ultrasound, wrench estimation, reachability, tool geometry.

1 Introduction

Ultrasound (US) imaging offers several advantages for diagnostic and interventional procedures. These include freedom from ionizing radiation, good soft tissue contrast, high flexibility, and real-time image acquisition. The combination of US imaging with a robotic system enables precise and repeatable automatic image acquisition, while ergonomically relieving sonographers and counteracting staff shortages [1].

The robotic system must meet two conditions to deliver high-quality US images. First, the target area must be well reachable by the robot. High maneuverability allows flexible adjustment of the probe's pose at the target, which could be necessary to compensate for small movements of the patient or to track the target in the US image. We demonstrated in [2] that the geometry of the probe holder strongly influences the reachability of target poses and thus could be optimized for specific scenarios. Second, the image quality of robotic US strongly depends on the contact force of the US probe [3]. Precise contact force control must therefore be ensured by the robot. In this work, the influence of the probe holder geometry on reachability as well as on the accuracy of the robot wrench estimation model is investigated.

2 Experimental setup

The experimental setup is shown in Figure 1. It consists of a gel phantom and a KUKA LBR 14 R820 robot with a Bota Systems Rokubi F/T sensor mounted on the end effector. A 3D printed model of the US probe is then attached with a corresponding probe holder geometry after the F/T sensor. With this setup, we can measure the ground truths of the forces and moments acting on the probe.

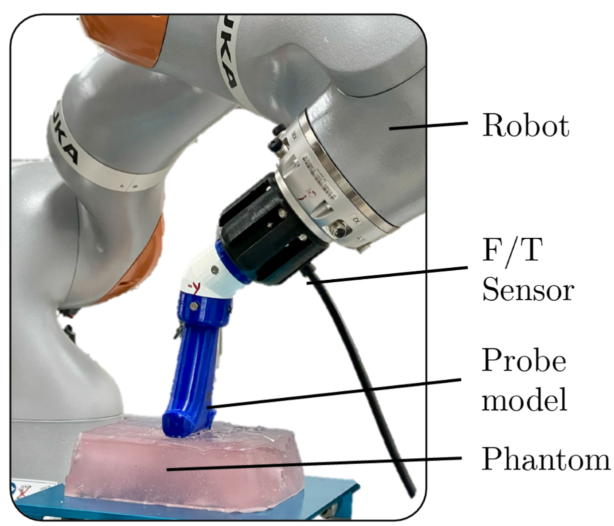

Fig. 1: Experimental setup, consisting of a gel phantom, a robot with the F/T sensor and the Tool 45° attached to the end effector.

2.1 Probe holder geometries

Four different geometries of the probe holders were used for the experiments, which were designed as 3D printed models

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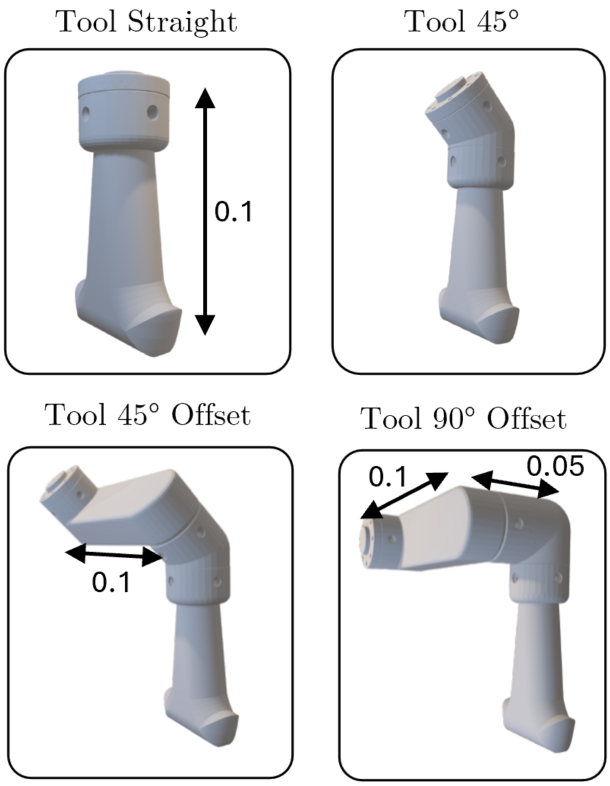

Fig. 2: Four different tool geometries were tested, which differ in their mounting angle and a lateral offset to the end effector.

(Figure 2). These include a straight extension of the F/T sensor by a distance of 10 cm, which is referred to as *Tool Straight* and considered as reference geometry. The second tool is attached to the sensor at an angle of 45° and named *Tool 45°*. In addition to this angulation, a translational offset of 10 cm is added to the geometry of the third tool, referred to as *Tool 45° Offset*. The fourth tool has a mounting angle of 90° and a translational offset of 10 cm and is labelled *Tool 90° Offset*.

2.2 Ultrasound path

To simulate a US examination, a specific path was defined, representing a combination of common US probe movements [4]. First, the probe was manually aligned normally to the phantom surface. Subsequently, to establish contact and generate a wrench, the probe was moved into the gel phantom for a small distance of 2 mm. Then, the probe was increasingly rotated outward, while the probe's center point remained at its origin. Thus, the probe's end towards the cable is moved on a spiral-shaped path with increasing radius (see Fig. 3). The movement is continued until the probe is tilted up to a maximum angle of 35°. This path was followed for each tool geometry at different locations in the front right quadrant of the robot's workspace. Thus, for each probe holder geometry, around 30,000 poses were approached. The joint velocities of the robot were limited to 2% of their maximum values to guarantee a slow probe movement, comparable to a real US examination.

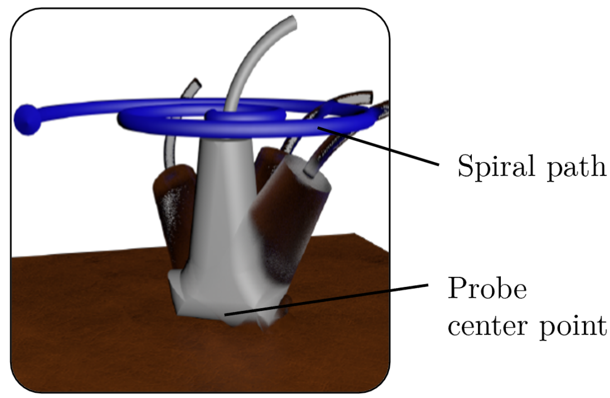

Fig. 3: Visualization of the spiral path, representing a US examination. The probe is gently moved into the phantom for 2 mm and then and then subjected to a controlled tilting motion. While the center of the probe remains fixed, the distal end of the probe - the end connected to the cable - is gradually rotated outwards until a maximum angle of 35° is reached.

2.3 Validation experiments

While following the paths, the joint configurations q and the external joint torques τ_{ext} were obtained through the robot's interface. The external joint torques τ_{ext} were estimated using the manufacturer's internal robot model. Moreover, the ground truth measurements of the F/T sensor, mounted between the probe and the end-effector, were recorded.

2.3.1 Reachability analysis

To analyze the reachability of the robot, the reachability values r_i of all approached poses i are calculated by

$$r_i = \sqrt{det(J(q_i) \cdot J(q_i)^T)}, \quad (1)$$

where J is the Jacobian and q_i the respective joint configuration [5]. For each probe holder geometry, the resulting reachability values are then analyzed using the representation of a normalized histogram. This allows a comparison of the distributions of the reachability values obtained for the different tool geometries for the selected US paths.

2.3.2 Wrench estimation accuracy

Since the probe was moved very slowly by the robot, a quasi-static movement can be assumed. The estimated wrenches $w_{est,i}$ were calculated by

$$w_{est,i} = \begin{pmatrix} f_{est,i} \\ m_{est,i} \end{pmatrix} = (J(q_i)^T)^{-1} \tau_{ext}, \qquad (2)$$

where $f_{est,i}$ represents forces and $m_{est,i}$ the moments applied and $J(q_i)^T$ is the transposed Jacobian [6]. The estimated wrenches are compared with the ground truth measurements obtained by the F/T sensor by calculating the Euclidean error. Thus, the performance of the different tools regarding the wrench estimation accuracy could be evaluated.

3 Results

The reachability values and the accuracy of wrench estimation for approaching the path poses were compared for the four different tool geometries. The sample sizes of the data, presented in the following Tables 1,2 and 3 were 30,909 for the Tool Straight, 36,369 for the Tool 45°, 35,153 for the Tool 45° Offset, and 22,794 for the Tool 90° Offset, respectively.

3.1 Reachability analysis

Histograms of the reachability values for the different probe holder geometries are shown in Fig. 4. The values are normalized with respect to the overall maximum reachability value. It can be seen that using the Tool 90° Offset for following the defined paths results in the highest concentration of configurations in the upper reachability range, with most values clustered in the highest quartile with a reachability value between 0.75 and 1. In addition, Table 1 shows the Tool 90° Offset has the highest mean and median reachability values. Moreover, it also has the highest minimum and maximum reachability values, thus outperforming the other tools in all metrics. Compared to the reference tool, represented by the straight extension of the end effector (Tool Straight), the mean reachability value is increased by 16%. The reference tool has the second-highest mean reachability, with a value of 0.75. Moreover, it can be seen in the respective histogram that almost a fifth of the poses can be approached with a very high reachability value of 0.9 (Fig. 4). In contrast, the Tool 45° as well as the Tool 45° Offset have considerably fewer poses with reachability values in such a high range.

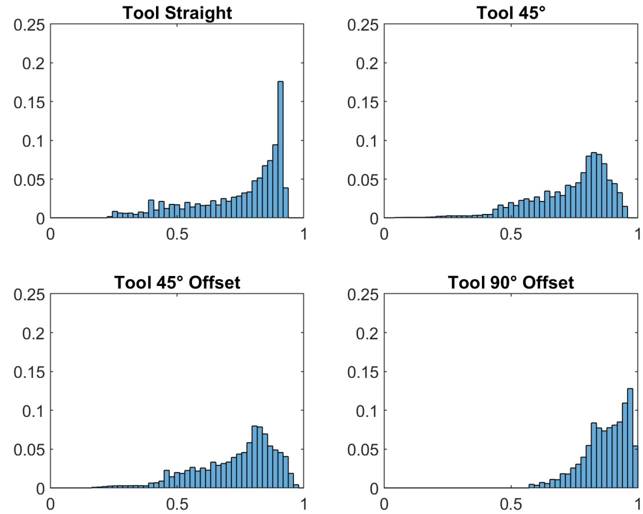

Fig. 4: Histograms of reachability values for all poses along the defined spiral paths, as approached by the robot using the four different probe holder geometries.

Tab. 1: Normalized reachability values for the different probe holder geometries.

Tool	Mean	Median	Std	Min	Max
Tool Straight	0.75	0.82	0.18	0.24	0.93
Tool 45°	0.73	0.78	0.15	0.05	0.96
Tool 45° Offset	0.73	0.78	0.15	0.16	0.97
Tool 90°	**0.87**	**0.89**	**0.09**	**0.58**	**1.00**

3.2 Wrench Estimation Accuracy

During the experiments, the F/T sensor recorded forces and moments in a range up to 85 N and 12 Nm, respectively. The Euclidean error between the F/T sensor's ground truth measurements and the robot's wrench estimation were calculated, separately, for the forces and moments for each tool geometry. As can be seen in Table 2 and Table 3, the Tool 90° Offset consistently achieved the lowest Euclidean errors, with a mean error of 9.5 N for force components and 1.3 Nm for moment components, outperforming all other tools. This tool also had the smallest standard deviation and the lowest maximum outliers. The second most accurate tool is the Tool Straight, with a mean force estimation accuracy of 12.2 N and moment estimation accuracy of 2 Nm. Moreover, it can be seen that the Tool 45° Offset, including a translational offset, leads to a more precise wrench estimation than the Tool 45° without any offset.

Tab. 2: Euclidean Wrench Estimation Errors - Forces [N].

Tool	Mean	Median	Std	Max
Tool Straight	12.2	13.0	4.8	23.0
Tool 45°	19.9	16.0	12.4	131.1
Tool 45° Offset	15.4	14.7	7.5	60.4
Tool 90°	**9.5**	**9.5**	**3.3**	**20.2**

Tab. 3: Euclidean Wrench Estimation Errors - Moments [Nm].

Tool	Mean	Median	Std	Max
Tool Straight	2.0	1.9	0.7	5.8
Tool 45°	2.1	2.0	1.0	21.6
Tool 45° Offset	2.1	2.0	0.8	8.6
Tool 90°	**1.3**	**1.2**	**0.4**	**2.6**

4 Discussion and Conclusion

This study evaluated the impact of different tool geometries on reachability and wrench estimation accuracy in robotic US. The results show that combining lateral offsets with angular adjustments can strongly improve the wrench estimation accuracy. The improvement in wrench estimation accuracy is due to two key factors: First, the Tool 90° Offset improves the reachability of the robot while following of the path, allowing it to reach highly inclined probe orientations more effectively. This makes it easier for the robot to avoid singularities that lead to large errors in wrench estimation.

Second, the lateral offset allows the 7th joint to be included in the wrench estimation process. By involving the 7th joint, the wrench estimation model gains an additional degree of freedom, allowing for a better distribution of forces and moments across the joints. This reduces the reliance on individual joints and minimizes errors caused by singularities or unfavorable configurations, leading to more precise and reliable force measurements. The influence of the 7th joint can be seen in particular when comparing the tools angled at 45°. The tool with the additional offset has lower errors in the wrench estimation than the tool without offset (see Table 2 and Table 3), while the reachability values for the two tools are almost the same (see Table 1).

The results demonstrate that tool geometry influences wrench estimation accuracy, because different geometries lead to different joint configurations along the same tool path. These configurations affect how the externally applied wrench is projected onto joint torques, and thus how well the robot's internal model can reconstruct the applied forces and moments. Tool designs that promote well-conditioned Jacobians enable more reliable wrench estimation without additional F/T sensors.

In the considered use case of robotic US scans, a translational shift of the tool is particularly suitable for this purpose, so that the 7th joint can also be included in the wrench estimation. It should be noted, however, that the results relate to the specific rotation paths in a selected area of the robot's workspace. For these, the 90° angled and translationally displaced tool has proven to be the best option to achieve a high level of reachability and wrench estimation accuracy. In the next steps, more varying paths would therefore have to be tested. Moreover, varying phantom stiffness could support future investigations on tool–tissue interaction under more diverse conditions.

Author Statement

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References

[1] von Haxthausen F, Böttger S, Wulff D, Hagenah J, García-Vázquez V, Ipsen S. Medical robotics for ultrasound imaging: current systems and future trends. Curr Robot Rep 2021;2:55–71.

[2] Osburg J, Nguyen NT, Ernst F. Increasing Reachability in Robotic Ultrasound Through Base Placement and Tool Design. Int J Med Robot 2025;21(1).

[3] Burcher M R, Noble J A, Han L , Gooding M. A system for simultaneously measuring contact force, ultrasound, and position information for use in force-based correction of freehand scanning. T-UFFC 2005;52(8):1330-42.

[4] Adams R B. Ultrasound scanning techniques. Surgery Open Science 2022; Volume 10.

[5] Yoshikawa T, "Manipulability of robotic mechanisms," The International Journal of Robotics Research, vol. 4, no. 2, pp. 3–9, 1985.

[6] Craig J J. Introduction to Robotics: Mechanics and Control. Prentice Hall, 3rd edition, 2005.