Pulse-echo test for medical imaging ultrasound probe and collaborative robot: performance and usability

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1. Introduction

Imaging probes for diagnostic ultrasonography are devices that generate a pressure field into the human body, according to an electrical signal. The differences in acoustic properties of different types of tissue allow the scanner to generate an image of a part of the body, based on the received echo signals. The quality of the resulting image is strictly related to the materials involved in the transducer manufacturing and the understanding of their interactions.

The transducer comprises of a standard piezoelectric ceramic, a hard rubber backing substrate, several (usually from one to four) acoustic matching layers and a silicon rubber lens.

A sketch of a typical transducer is reported in Fig. 1.

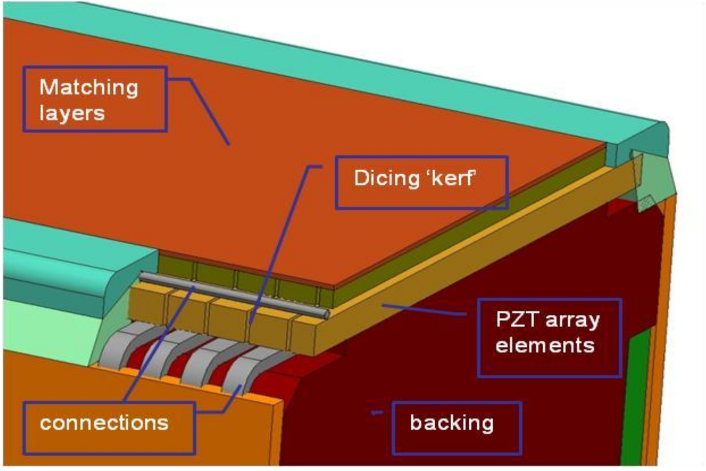

Fig. 1: Transducer sketch.

2. Pulse-echo measurement

The most important and characterizing electroacoustic measurement for an ultrasound imaging probe consists in the pulse-echo measurement from each single array element, which allows to get information on pulse waveform and bandshape quality and amplitude. Many important aspects of the performances of a probe can be tested, such as image quality (SNR), maximum depth of diagnostic applications, multiple frequencies of operation and many others. A picture of a typical pulse-echo measurement test-bench is shown in Fig. 2.

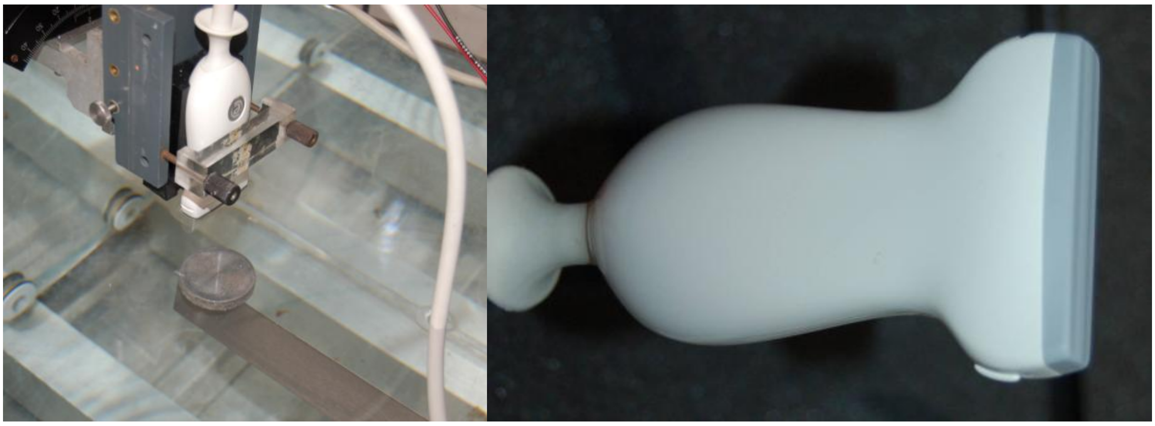

Fig. 2: Pulse-echo measurement test-bench (left) and a typical complete probe head (right), with silicon lens and plastic covers.

The pulse echo measurement consists in simply receiving an ultrasound pulse sent into a water tank from the probe itself and reflected from a metallic target, the transducer being driven by a specialized pulser/receiver device. The pulse

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waveforms are typically displayed on an oscilloscope and analysed on a PC. Water is typically used as the medium in this kind of measurements since its acoustic properties (like ultrasound velocity) match body tissues ones. The relative position and the alignment between transducers and metallic target into the water tank are key points that can affect the reliability, accuracy and repeatability of the measurements. The temporal distance between the probe and the target is called *time of flight* and usually this distance should be equal to the focal distance of the probe as, in this position, the echoed signal reaches its maximum value. Therefore, before the measurement starts, an accurate positioning of the probe into the water tank is required especially in Z-direction (perpendicular to the top target surface). In addition, the probe position is adjusted also with regard to rotation around the azimuth and elevation directions if a convex abdominal probe is under test. This procedure aims to eliminate *time of flight* variations among all the elements of the probe caused by a misalignment between probe and target. Additionally, it also ensures the optimal angle of incidence of the ultrasonic waves on the reflector.

So, the pulse-echo test is the key in-process test adopted from all the worldwide probe manufacturers included Esaote SpA as quality control, production final test and engineering of probes. Therefore, it is crucial to design a pulse-echo tester in order to limit the variability of the equipment in terms of reproducibility, repeatability (i.e. *GageR&R*<10%) and a labor time for an acceptable efficiency of the probe manufacturing process.

Commercial ultrasonic pulse-echo testers available in the market show poor automation features and they are operator dependent because probe positioning is typically performed by an operator visually inspecting the echo signal displayed on the oscilloscope, and manually translating and orienting the probe through linear guides. Consequently, the performance, both in terms of operating cycle time and reproducibility, are scarce, especially when the measurement system is expected to work in a production environment (in-process quality control for probe large mass production). Quantitative data obtained with pulse-echo tests are essential also for controlling the statistical process so they should minimally be affected by the variability of the tester itself.

Among the actions which can be taken for improving repeatability and reproducibility of measurement system and also for reducing the cost of the test by reducing labor time, which consists essentially of eliminating dependence by test on operators adopting, for example, a precision linear stage[3] coupled with precision goniometers[4], a collaborative robot could be an attractive and performing solution. A standard solution as [34] provides very precise movements in terms of reproducibility and repeatability but it is very expensive and it doesn't have very good performances in terms of velocity. Furthermore, it is a classic solution where all the system is closed with respect to the operator. So it is very hard to provide to the operator the possibility to inspect the process (e.g. it is useful for the operator to see the probe when it is in the water to remove the air bubbles from the probe's surface). An attractive and performing solution is represented by the use of a collaborative robot. There are several reasons that drive many industries to adopt collaborative robots in their production areas. The most important reason is represented by the possibility to allow human operator to work alongside the robot without the need of providing external technologies to guarantee safety. In this scenario, the human can perform all the highly precise manipulation tasks, by visually monitoring the process and easily interacting with the robot.

All the repetitive tasks, covering actions requiring a low level of know-how, are demanded to the robot increasing the productivity of the process.

Being the present work a feasibility study, its purpose was to verify if a collaborative robot could make it possible to execute the expected probe positioning into the water tank with the expected performances in terms of spatial resolution for all the degrees of freedom used for probe alignment during the test.

A collaborative robot (UR5) from Universal Robots, in combination with a Schunk gripper (WSG – 050-210B) equipped with custom fingers were adopted and the performances were compared to a commercial manual probe alignment water tank (Fig. 3).

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[3] https://www.physikinstrumente.com/en/products/linear-stages-and-actuators/stages-with-motor-screw-drives/l-509-precision-linear-stage-1201903/

[4] https://www.physikinstrumente.com/en/products/rotation-stages/stages-with-worm-gear-drives/wt-85-motorized-precision-goniometer-1206600/

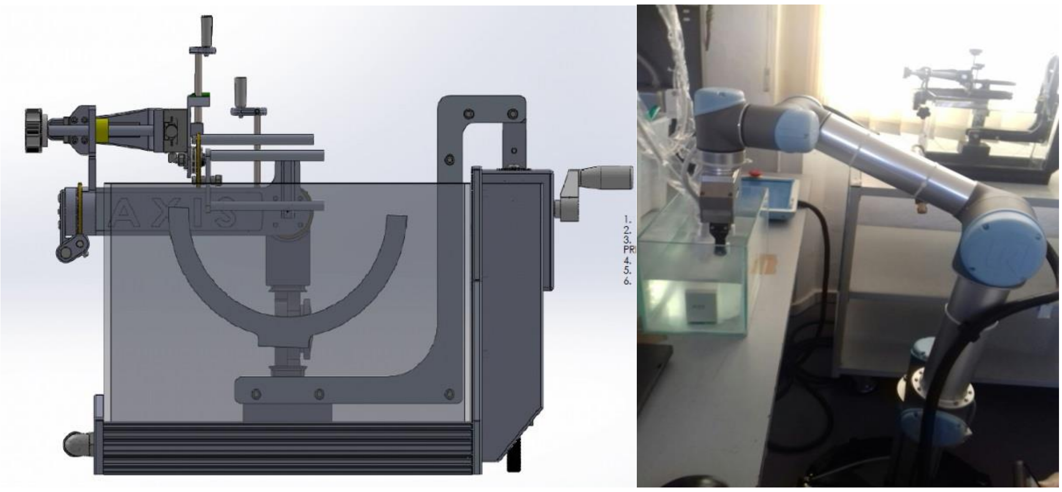
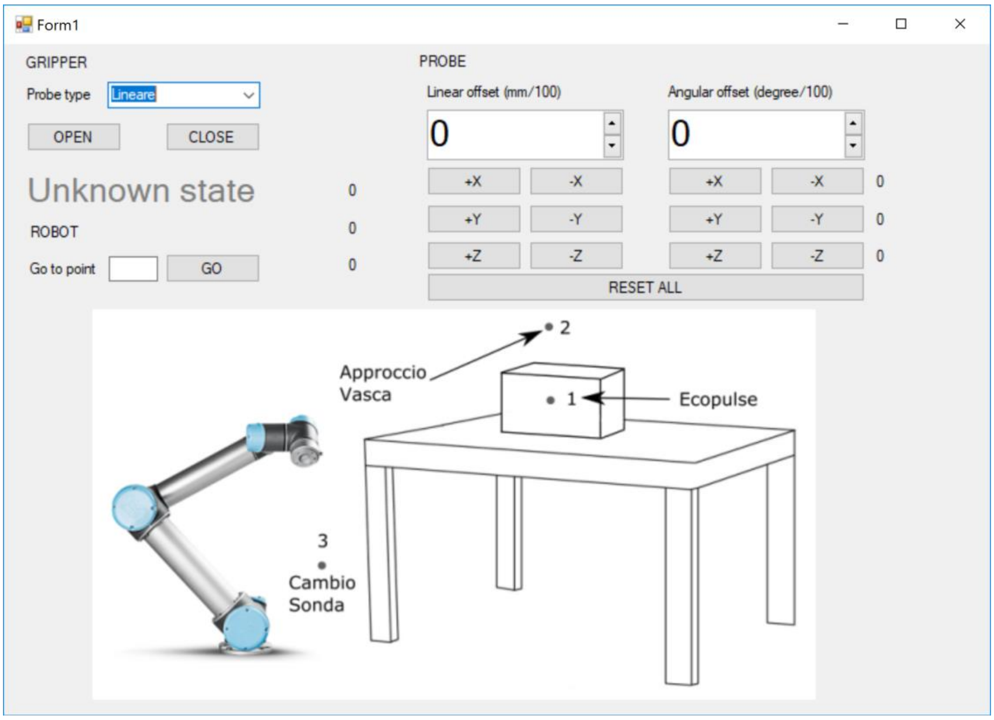


Fig. 3. Commercial probe alignment water tank manual mechanic (left), and the UR5 with gripper Schunk WSG-050-210-B (right).

The robot was controlled by means of a PC based software (the GUI is depicted Fig. 4) on which the user can sets the following parameters/actions:

- select the probe type to test;
- open or close the Schunk gripper;
- positioning the robot in different test points;
- set amplitude and direction of translational and rotational movements.



Form1

GRIPPER

Probe type: Lineare

Unknown state

PROBE

Linear offset (mm/100): 0

Angular offset (degree/100): 0

Fig. 4. GUI of the software designed to drive the collaborative robot.

As show in GUI (Fig. 4) the software can perform three type of adjustment for linear offset and three for angula one. In Fig. 5 it is showed all types of offset.

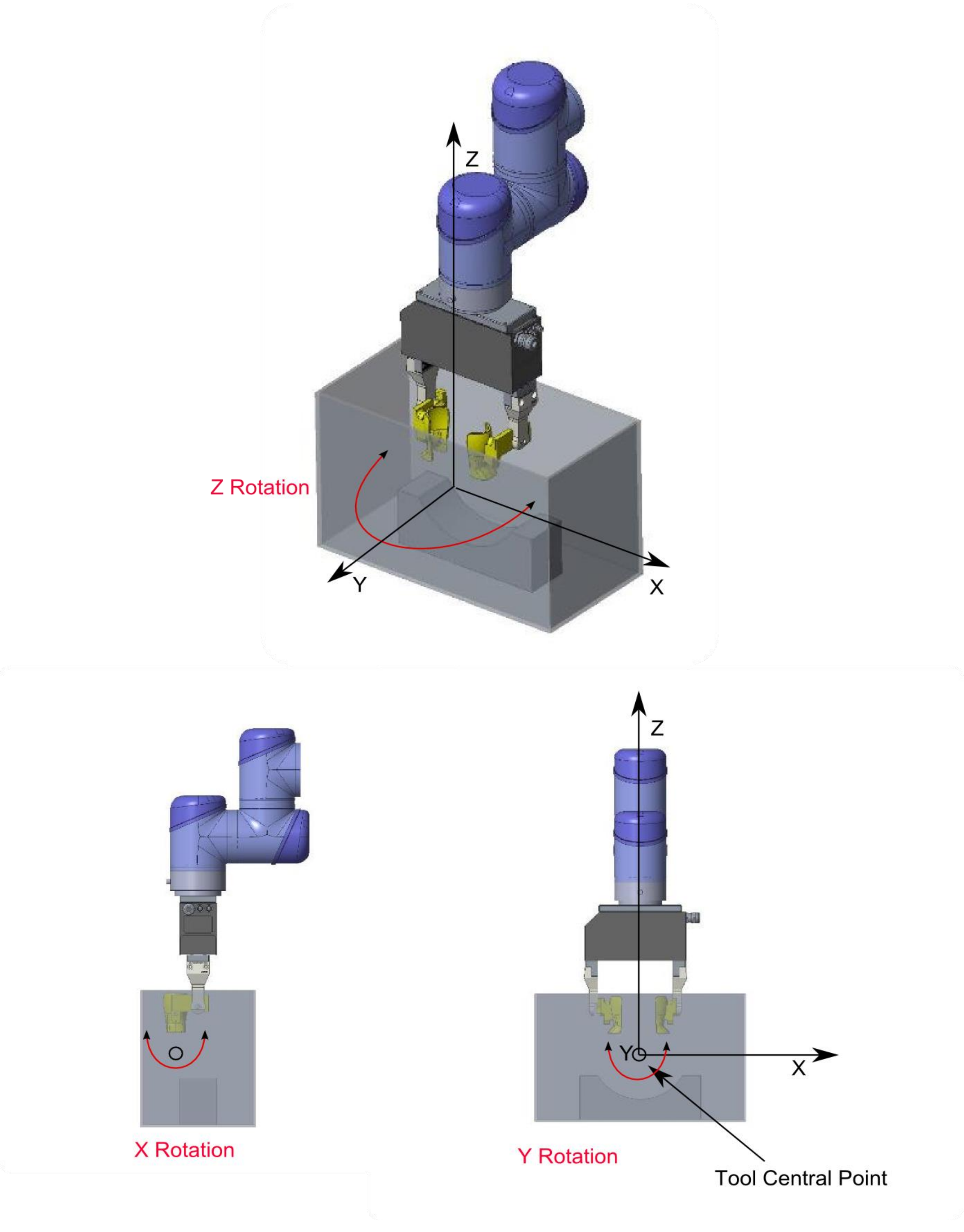


Fig. 5: 3D model of the UR5, the gripper, custom fingers, water tank and target; Translations and the rotations of Tool Central Point are coloured in BLACK and in RED respectively..

The probe used for the test is the Esaote abdominal probe called AC2541 (R50 convex array, 192 elements, 3.5 MHz nominal frequency).

Fig. 6. The AC2541 abdominal probe used for the feasibility study.

The rationale for choosing this specific probe is the (relative) difficulty of the alignment procedure (more difficult with respect to a linear probe due to its curvature).

Fig. 7. UR5 with WSG performing an ECO pulse test.

The measurements were performed by pulsing each probe's element with a single sine cycle (3.5 MHz) by means of a 50 Ohm Function Generator (Agilent) and recording for each element both the RF excitement pulse and the Received Echo signal generated by a R80 reflector at 3 cm distance from the array surface.

Fig. 8 shows measurement from a fully manual (A, B, C) and automated (D, E, F) test. Three different measurements are performed: RF received signal (Pulse), averaged over 192 elements of the probe for each measurement Pulse Envelope (magnitude of Hilbert's transform of Pulse), Spectrum (magnitude of the FFT of the Pulse). Several parameters were compared, both analysing the average curves and sensitivity variation of the elements on the array evaluated.
A Repeatability Evaluation comparing the fully manual vs. manually driven Robot approaches was performed by repeating the test 5 times for each configuration using the same Transducer.

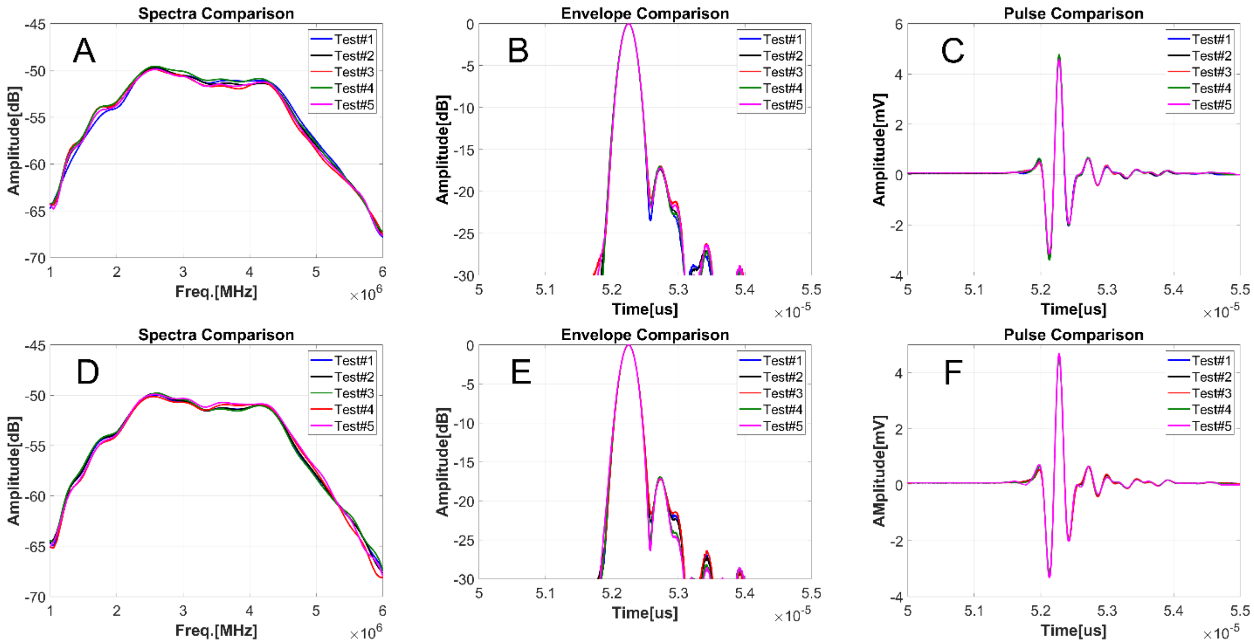


Fig. 8. RF received signal (Pulse), averaged over 192 elements of the probe for each measurement Pulse Envelope (magnitude of Hilbert's transform of Pulse), Spectrum (magnitude of the FFT of Pulse). Manual measurement (A, B, C) and automated measurement (D, E, F)

At the end of the test, the probe was removed from the water tank. Thus, the positioning of the probe was repeated every time to test the reproducibility and repeatability of this task by the robot and the gripper and compare it with the manual procedure. Indeed, the same sequence was repeated for the manual tank with CERTARE tool.

Test responses, which were considered critical to quality for the analysis, are: array Mean sensitivity@3.5MHz, array VppMAX/MIN variation and Average Bandwidth@-6dB of 192 channels.

A final test was carried out to assess how the repeatability performance of the robot changes if the final position of the probe (i.e. the test position) was saved (recorded) and then recalled during following repetitions of the test (see on Fig. 9 the flow chart which explains the test procedure used in this study). This is another advantage of the automated alignment approach, which is practically impossible if manual mechanisms are adopted.

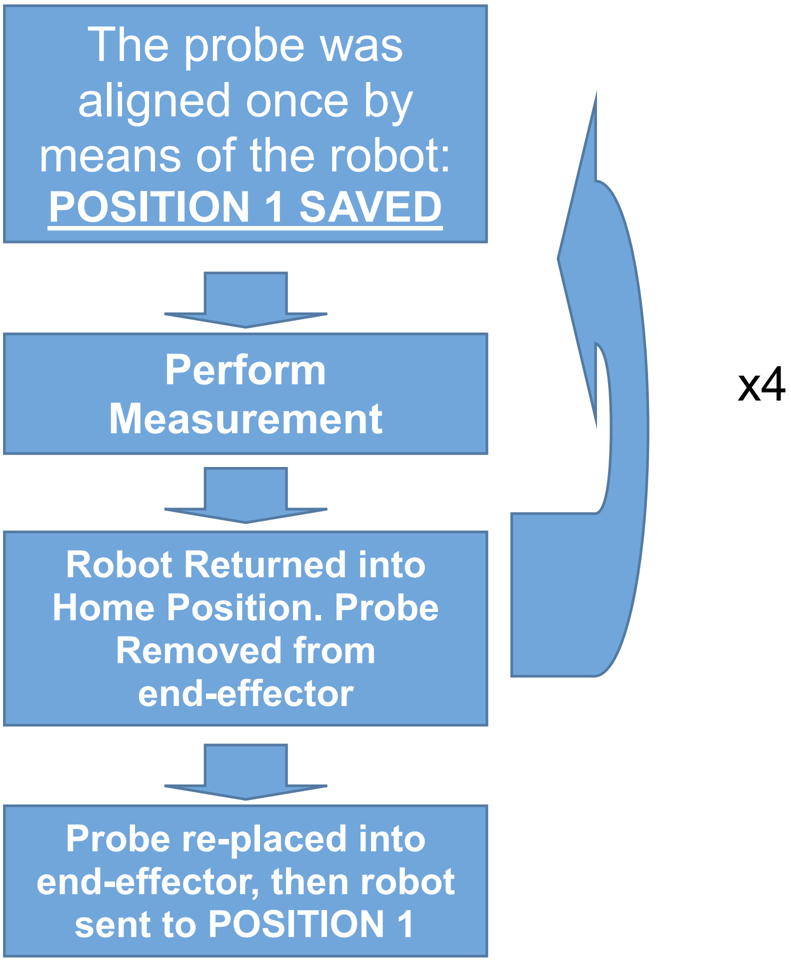


Fig. 9: Flow chart describing the step-by-step procedure adopted for the test when robot was asked to record the first final position.

As a preliminary study, a test for equal variances was considered in order to quantify the amount of variance obtained with the three measurement approaches (manual, UR5 and UR5 + recorded first alignment).
For the three responses, the individual plot shows the five single measurement values related to each test approach and the blue line connection between Means. The diagram of the equal variance test depicts 95% Bonferroni Confidence Intervals for Standard Deviations of the three alignment approaches under test.

Test for Equal Variances: Mean Sensitivity (dB)MANUAL; Mean S (dB)_UR5; Mean S (dB)_UR5+Align

```
Method

Null hypothesis          All variances are equal
Alternative hypothesis   At least one variance is different
Significance level       α = 0,05


95% Bonferroni Confidence Intervals for Standard Deviations

               Sample  N     StDev            CI
   Mean S (dB)_MANUAL  5  0,207364  (0,0547688; 1,50636)
      Mean S (dB)_UR5  5  0,089443  (0,0178297; 0,86087)
Mean S (dB)_UR5+Align  5  0,043301  (0,0097020; 0,37079)

Individual confidence level = 98,3333%


Tests
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                           Test
Method                Statistic  P-Value
Multiple comparisons          —    0,076
Levene                     1,78    0,210
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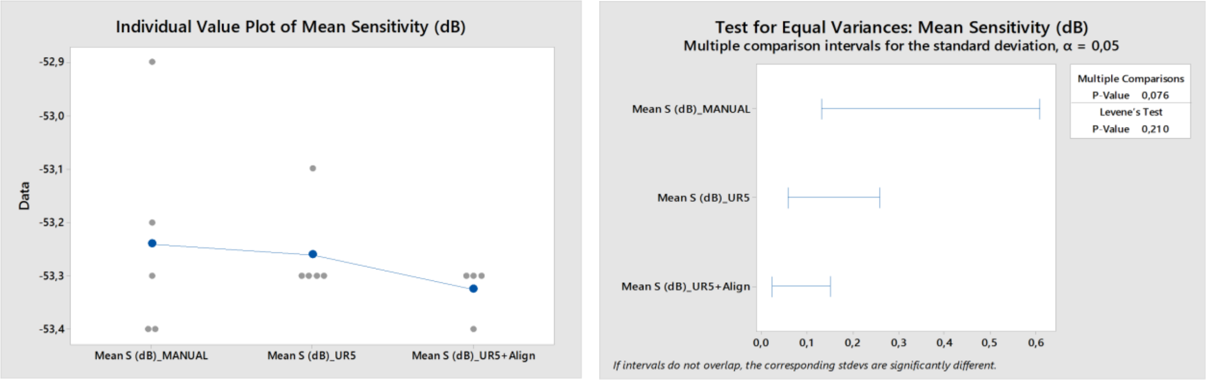

Figure 10. Comparison between the three investigated probe positioning approaches for Mean Sensitivity parameter by Individual value plot (left) and test for equal variances (right).

Test for Equal Variances: VppMAX/MIN variation (dB)

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Method

Null hypothesis         All variances are equal
Alternative hypothesis  At least one variance is different
Significance level      α = 0,05


95% Bonferroni Confidence Intervals for Standard Deviations

                    Sample  N     StDev             CI
   Global Disp (dB)_MANUAL  5  0,461519  (0,162094; 2,52119)
      Global Disp (dB)_UR5  5  0,230217  (0,065988; 1,54099)
Global Disp (dB)_UR5+Align  5  0,150000  (0,035985; 1,19966)

Individual confidence level = 98,3333%


Tests

                           Test
Method                Statistic  P-Value
Multiple comparisons          —    0,123
Levene                     2,24    0,149
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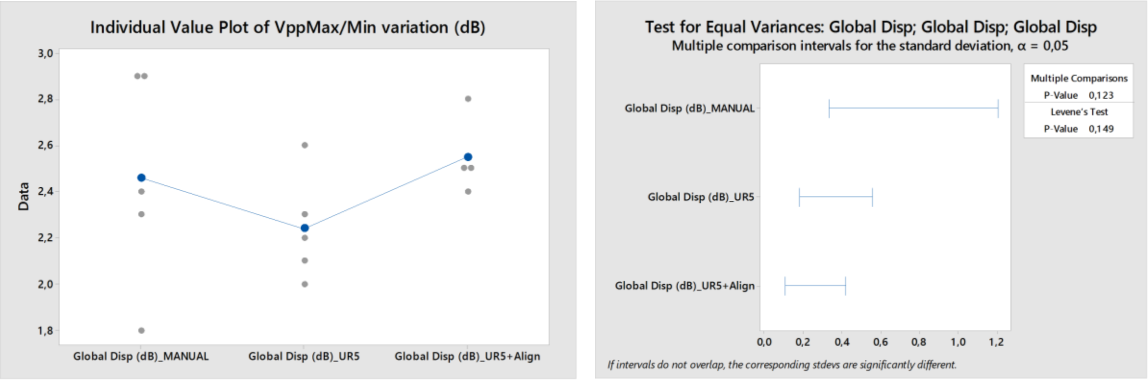

Figure 11. Comparison between the three investigated probe positioning approaches for VppMAX/MIN variation parameter by Individual value plot (left) and test for equal variances (right).

Test for Equal Variances: BW %_MANUAL; BW %_UR5; BW %_UR5+Align

```
Method

Null hypothesis         All variances are equal
Alternative hypothesis  At least one variance is different
Significance level      α = 0,05


95% Bonferroni Confidence Intervals for Standard Deviations

        Sample  N    StDev            CI
   BW %_MANUAL  5  1,81659  (0,779210; 8,12553)
      BW %_UR5  5  0,54772  (0,277587; 2,07355)
BW %_UR5+Align  5  0,86603  (0,194041; 7,41584)

Individual confidence level = 98,3333%


Tests

                              Test
Method                   Statistic  P-Value
Multiple comparisons             —    0,046
Levene                        1,94    0,187
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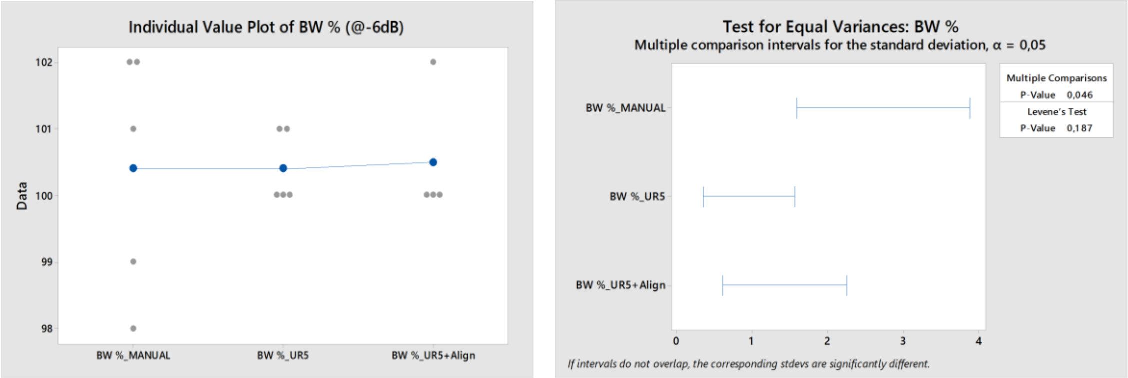

Figure 12. Comparison between the three investigated probe positioning approaches for BW(%) parameter by Individual value plot (left) and test for equal variances (right).

Despite the p-value is > 0.05 for the three responses (confidence intervals overlap), which means variances of the three test approaches are not statistically different, the statistical test for equal variances clearly indicates (Fig. 10, 11 and 12) that the UR5 robot together with the WSG gripper allowed to reduce the variability of the measurement system. This result has been obtained thanks to the higher repeatability of the collaborative robot when compared to the manual approach in positioning the probe. This result is also supported by looking at the graphs from the individual value plot.
Despite a sample size of 5 measurements may not be considered sufficient for a significant statistical test the study here reported clearly suggest that the use of a collaborative robot to test the pulse-echo probe may open to tangible advantage in terms of performance.. A further investigation increasing the number of measurements to at least 30 would be necessary to confirm the results.

3. Conclusion

The aim of the present work was to preliminarily test if a collaborative robot equipped with an electric gripper would be able to execute the probe alignment during pulse-echo test better than the manual approach. Only a preliminary repeatability test was performed (by performing the test with the same probe for several times).

The results showed how the automatic alignment method allowed to reduce the variability of the measurement system due to higher repeatability performances of collaborative robot compared to the manual approach (with a trained operator) when probe positioning is performed.
The automatic re-positioning test (loop depicted in Fig. 9) showed also that if a good alignment is achieved once with a probe and the position is "saved", the robot is capable of reproducing a position which is really close to the optimal one, so in this case, only small adjustments would be needed to perform a series of good measurements. This would result in a smaller variability of the pulse-echo measurement system and in reduced test cycle time, which is an advantage in case of probe in-process check in a production environment.

Future work will be focused on executing a complete GageR&R test (reproducibility and repeatability) in order to validate the new test setup allowing for its implementation in the probe manufacturing plant located in Florence (Italy).
A collaborative solution could be used in different phases of the probe production, and specifically in all phases where the humans have to position the probe near a target to test particular functionalities of the probe. The solution as presented here could be adapted to all those situations. The aim will be to increase the productivity in terms of performance of the operator but also in terms of reducing all hidden costs, such as assembly problems, reduction of refuses and early interception of the problems during production.