Project Acronym:

FUSROBOT(ENTERPRISES/0618/0016)

MRI-guided focused ultrasound robotic system for preclinical research.

Deliverable number: 4.2

Title: Evaluation of the motion of the robotic system using MRI imaging.

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Executive summary

In this deliverable (D4.2) the accuracy of the motion of the 2 DOF robotic system and 4 DOF is described. The accuracy of the motion was tested using digital calipers with a special designed set-up. Initially, the 2 DOF and 4 DOF robotic devices are briefly explained. More importance is given to the motion of each robotic device. Special additional parts were designed in order to secure the digital caliper at fixed position and obtain accurate measurements. The whole experimental set-up with the software is explained. The accuracy of the motion in both Y and X axis was estimated at step movements of 1 mm, 5 mm and 10 mm. The error of the motion of the robotic device in both axes as well as the speed of the motion was also calculated. The speed of motion of each stage was measured. In the second year we plan to evaluate the accuracy of the Z and Θ axis. During the experiments in phantoms, excised tissue and animal, the Z and Θ was not needed. Therefore, the delay in assessing their accuracy did not affect the progress of the project.

Two DOF robotic system

For small animals (mice and rats) that require a strong magnet (7 T) a smaller robotic system was designed. The robotic system includes two axes (X and Y) since the size of the animal is small and thus no Z axis is needed. The CAD drawing of the fully assembled 2 DOF robotic device with the motors (USR30-S3N, Shinsei Corporation, Kasuya Setagaya-ku, Tokyo, Japan) is shown in Figure 1. All the components which have been assembled to develop the robotic system are fully described in detail in Deliverable 3.2 (Two DOF robotic system).

Figure 1: CAD drawing of the 2 DOF robotic system for small animals.

The most important motions of the robotic device are the X and Y stages which can be performed using the corresponding software. There are some dimensional limits due the geometrical design of the robotic system. The maximum distance the transducer holder can move from one end to the other in the X axis and in the Y axis direction is 48 mm.

Four DOF robotic system

The fully assembled 4 DOF robotic device with the motors (USR30-S3N, Shinsei Corporation) is shown in Figure 2. All the components which have been assembled to develop the robotic system are fully described in detail in Deliverable 3.1 (Four DOF robotic system). The developed robotic device was designed with four PC-controlled stages. The robotic system includes three linear stages (X, Y, and Z axis) and one angular axis (Θ). Figure 2 shows the CAD drawing of the 4 DOF robotic system.

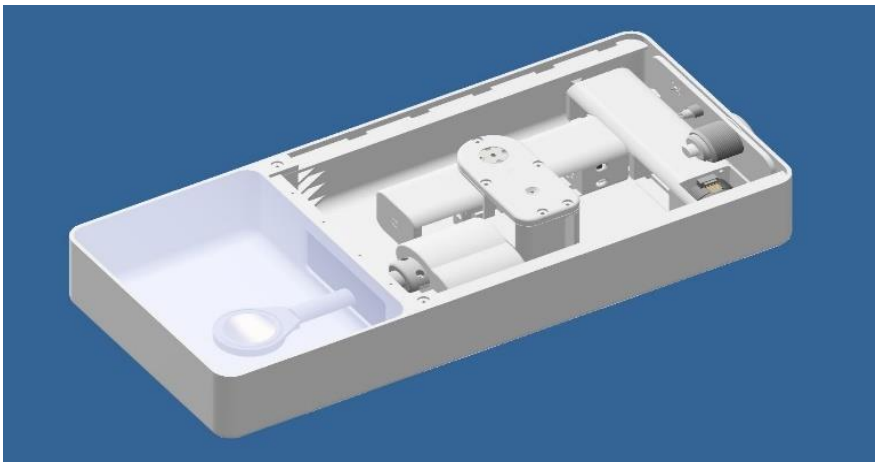

Figure 2: The 4 DOF robotic system with small motors.

There are some dimensional limits due the geometrical design of the robotic system. The maximum distance the transducer holder can move from one end to the other in the X axis is 29 mm, in the Y axis is 31 mm, in the Z axis is 39 mm and in the Θ axis is ±90^{o}.

Evaluation of the motion of the 2 DOF robotic system using a digital caliper

The accuracy of the motion of the 2 DOF robotic system was evaluated using a digital caliper (ROHS NORM 2002/95/EC) and a special designed set-up. The special designed set-up was developed in order to secure the digital caliper and to measure more accurately the linear motion of the robotic system in both axes (X and Y axis). The set-up is a 3D printing material (ABS-Acrylonitrile Butadiene Styrene) and it was printed using a 3D printer (F270, Stratasys, 7665 Commerce Way, Eden Prairie, Minnesota, 55344, USA). Figure 3 shows the digital caliper and Figure 4 shows the CAD drawing of the parts that were designed to evaluate accurately the motion of the robotic system. These parts can be easily attached to the robotic device.

Figure 3: Digital calliper that was used to evaluate the motion of the robotic systems.

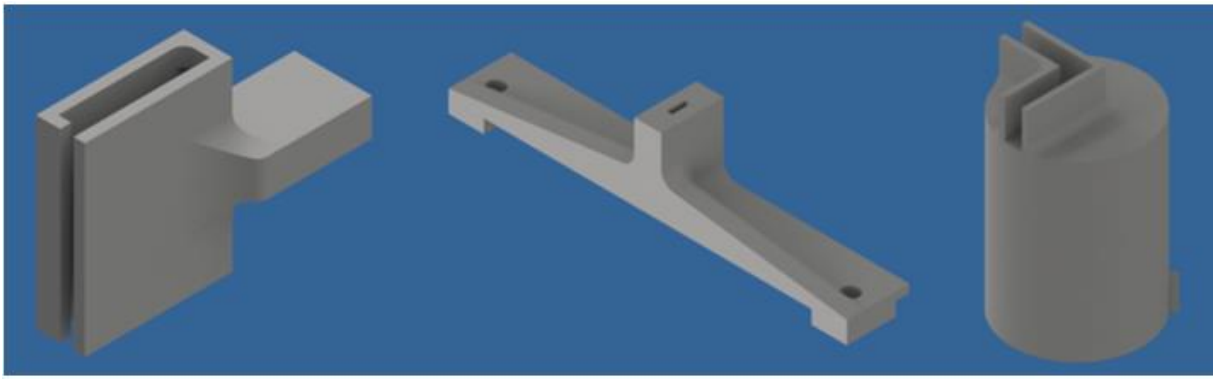

Figure 4: CAD drawings of the parts that were used to evaluate the motion of the robotic device.

Figure 5 shows the drawing of the set-up that was used to estimate the accuracy of the X axis motion attached to the robotic device and Figure 6 shows the drawing of the set-up that was used to estimate the accuracy of the Y axis motion of the robotic device.

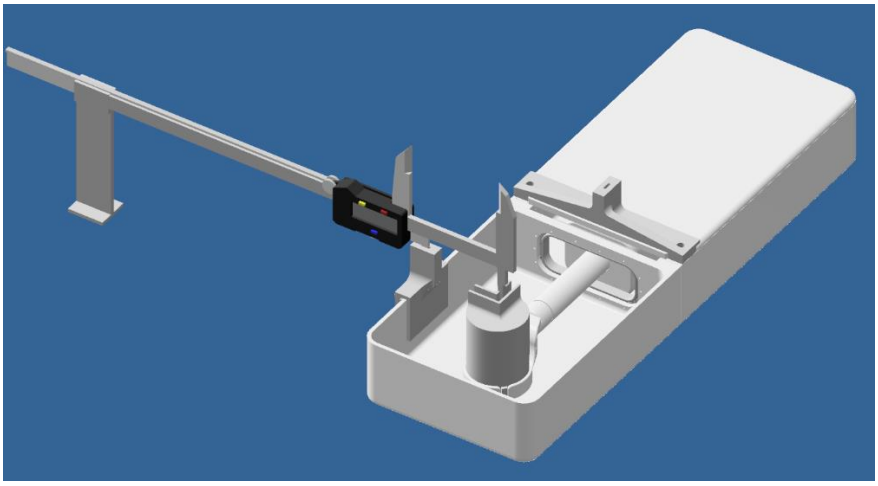

Figure 5: CAD drawing of the set-up that was used to estimate the accuracy of the Y axis motion.

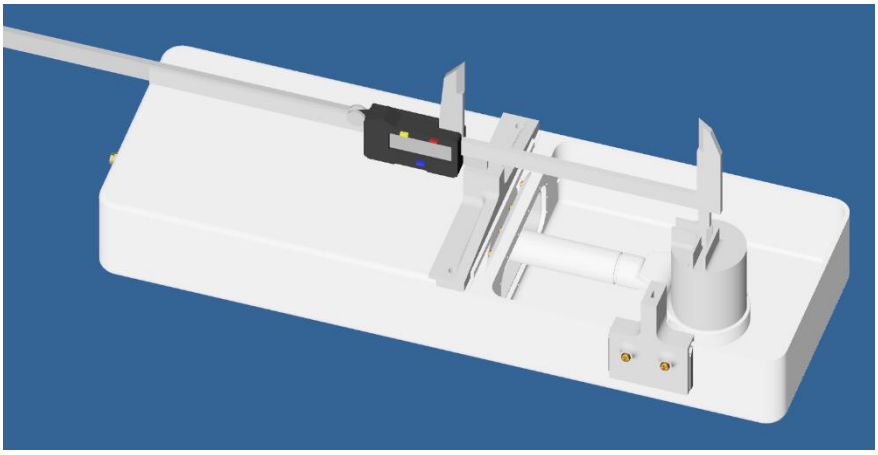

Figure 6: CAD drawing of the set-up that was used to estimate the accuracy of the X axis motion.

The piezoelectric motors and the encoders of the robotic device are connected through the electronics of the robotic device to a software that was developed (Figure 7). The software has many capabilities including the motion of the robotic device. Basically, measuring the precision of the robotic system controls the accurate motion of the piezoelectric motors and the correct reading of the motion by the encoders. The experimental set-up is shown in Figure 8.

Options to move the robotic device

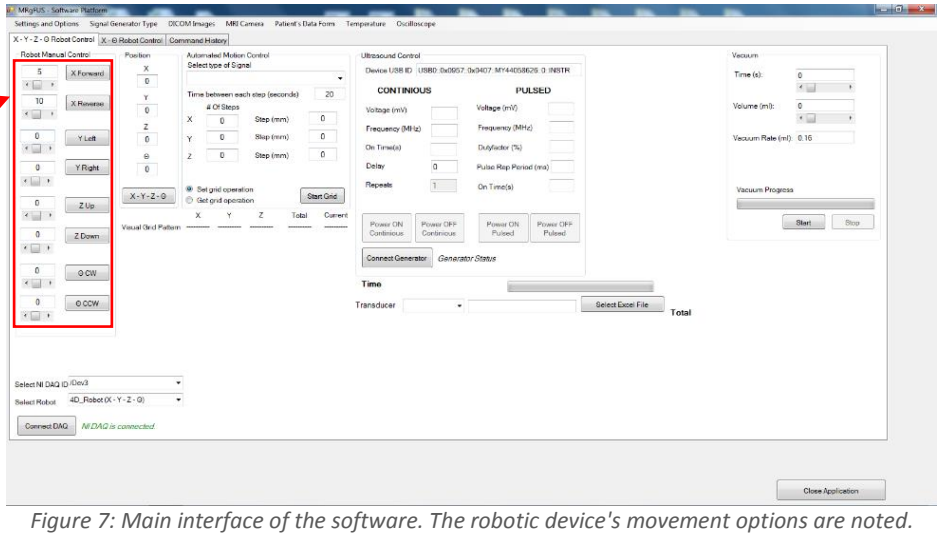

Figure 7: Main interface of the software. The robotic device's movement options are noted.

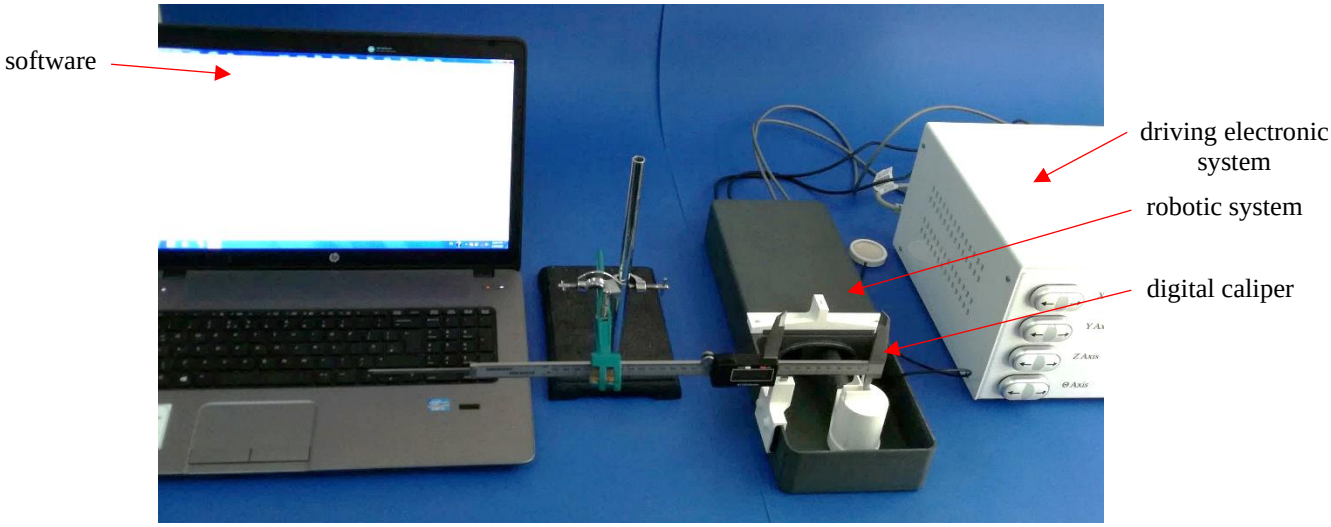

Figure 8: Experimental set-up in order to evaluate the motion of the robotic device.

The accuracy of the motion in the X axis was evaluated as shown in Figure 9. The robot was moved using the software at a certain distance and the actual distance of the motion was recorded using the digital caliper. Motion steps of 1 mm, 5 mm and 10 mm were evaluated. Table 1 lists the actual measured distance at motion steps of 1 mm, 5 mm and 10 mm for the X axis. Figure 10 shows the actual measured distance versus the intended distance for the X axis forward motion and Figure 11 shows the actual measured distance versus the intended distance for the X axis reverse motion.

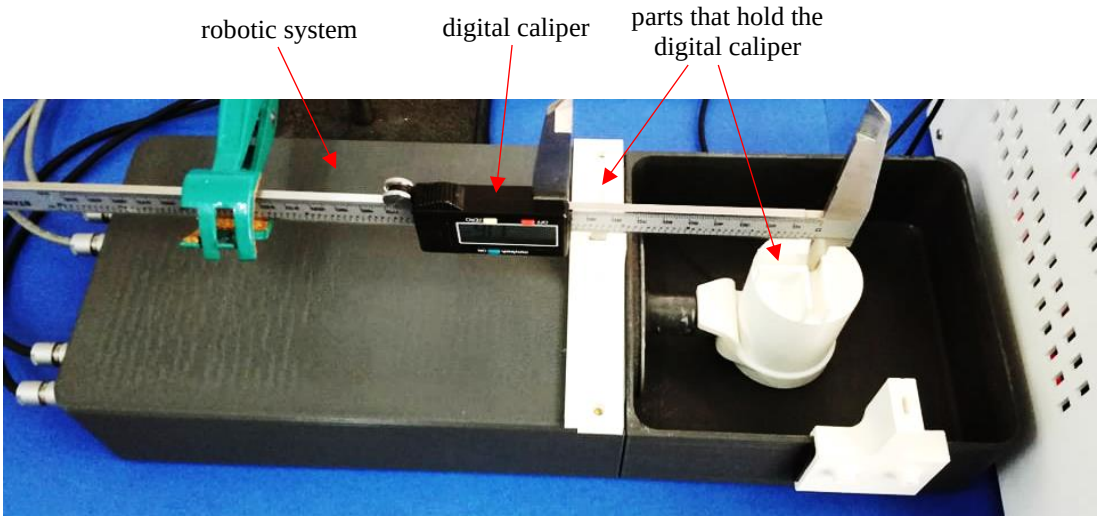

Figure 9: Evaluation of the motion of the robotic device in the X axis.

Table 1: List of distance measurements taken at motion step of 1, 5 and 10 mm for the X axis evaluation.

Intended distance (mm)	**1**		**5**		**10**	
Measurement number	**Distance moved forward (mm)**	**Distance moved reverse (mm)**	**Distance moved forward (mm)**	**Distance moved reverse (mm)**	**Distance moved forward (mm)**	**Distance moved reverse (mm)**
1	1.02	1.04	4.96	4.89	10.08	10.02
2	0.96	1.05	4.95	4.95	9.92	9.99
3	1.04	1.02	4.95	4.98	10.11	9.97
4	0.96	0.9	4.9	4.75	9.98	10.11
5	1	0.93	4.94	4.92	10.04	9.96
6	1.03	1.02	4.92	4.87	9.99	10.10
7	0.95	1.03	4.87	4.74	10.04	9.96
8	0.98	0.98	4.9	4.95	10.02	10.09
9	0.95	1.01	4.97	5.04	10	9.99
10	0.99	0.94	5.05	5.05	10.05	10.07
11	0.93	0.91	4.87	4.98	10.03	10.03
12	0.99	1.03	5.1	5.02	9.99	10.02
13	0.89	0.93	4.84	5.16	10.04	9.98
14	0.99	0.9	5.06	4.88	10.02	10.05
15	0.99	1.05	5.11	4.91	9.98	10.01
16	1	1.08	5.09	4.85	10.09	9.99
17	0.94	1.06	4.91	4.99	10.05	10.09
18	0.96	0.98	4.95	4.99	9.97	10.01
19	0.94	0.93	4.95	5.06	10.04	10.03
20	1.06	0.92	4.96	4.92	10.04	9.97
Average	**0.9785**	**0.9855**	**4.9625**	**4.945**	**10.024**	**10.022**

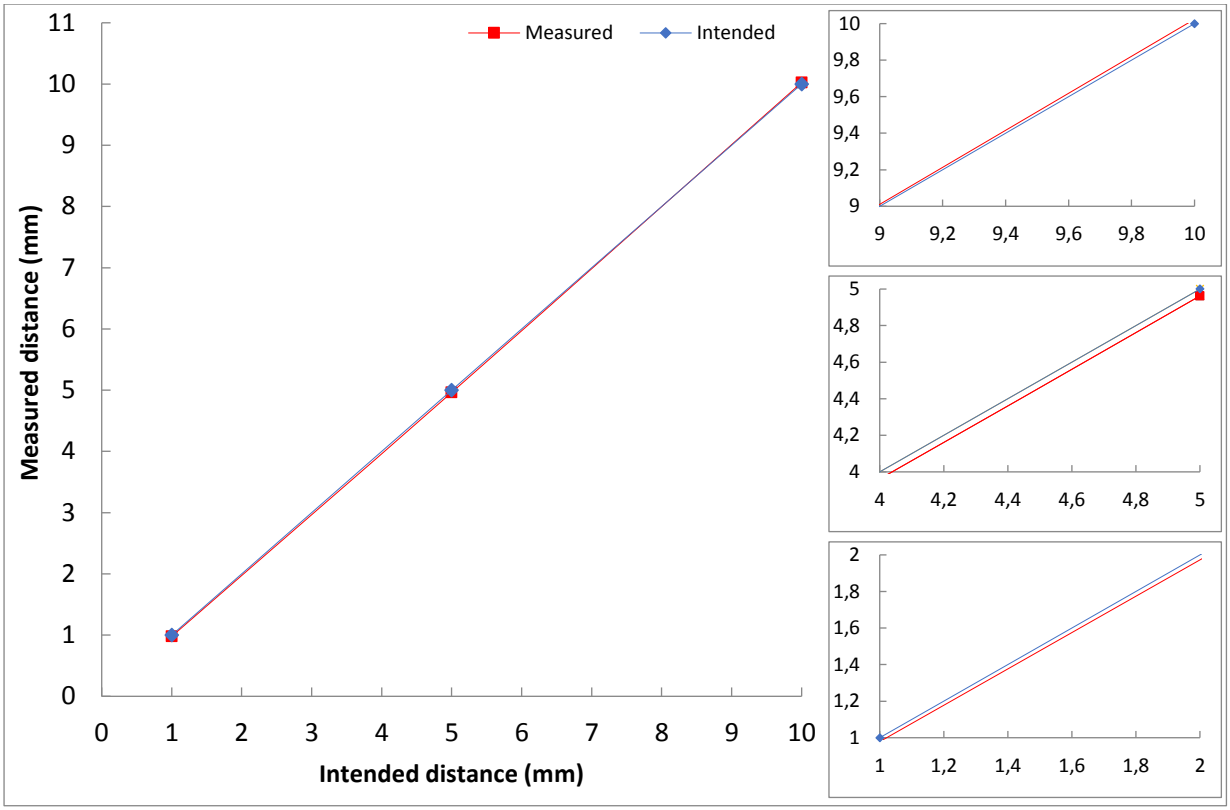

Figure 10: Measured distance versus intended distance for the X axis forward motion (left) and zoomed areas of the graph (right).

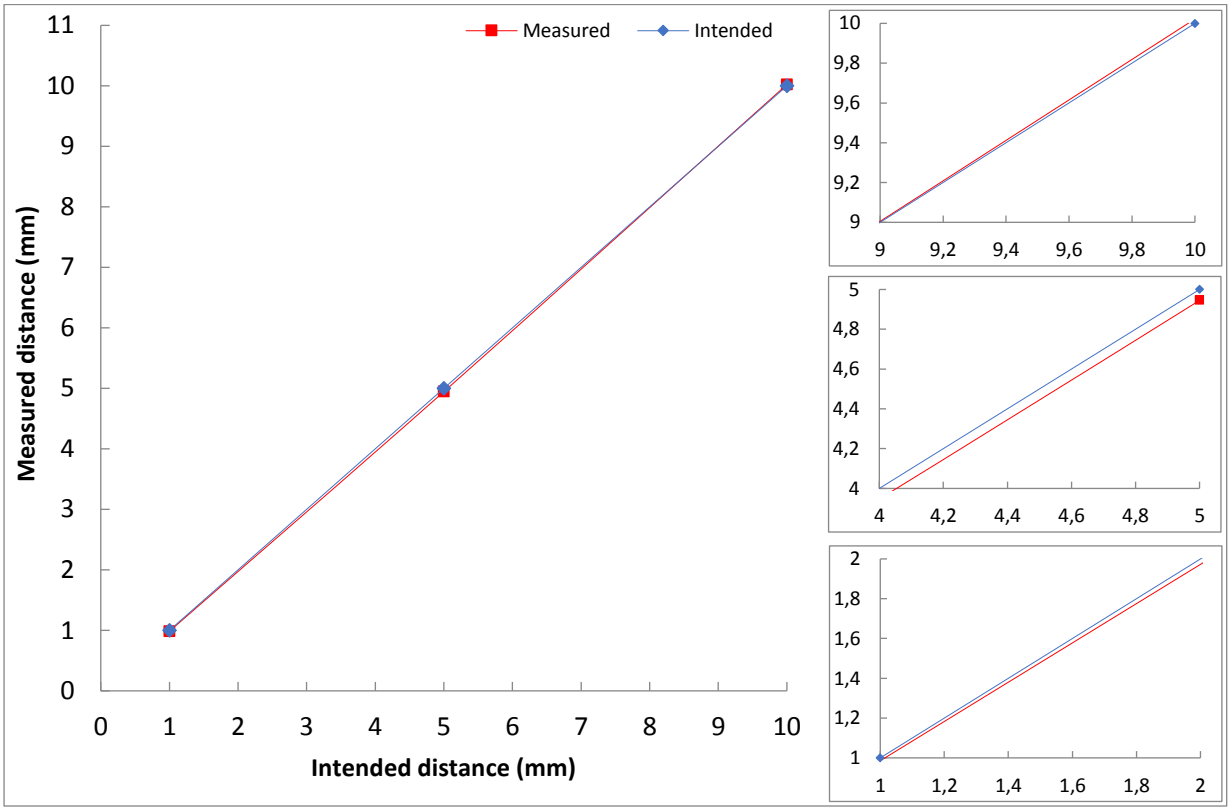

Figure 11: Measured distance versus intended distance for the X axis reverse motion (left) and zoomed areas of the graph (right).

The error at each step movement of the robotic device was estimated for the X forward and reverse motion. Table 2 summarizes the error measured at motion steps of 1 mm, 5 mm and 10 mm for the X axis forward and reverse directions.

Table 2: List of error estimated at different motion steps for the X axis forward and reverse directions.

Step (mm)	Error-forward motion	Error-forward motion (%)	Error-reverse motion	Error-reverse motion (%)
1	0.0215	2.15	0.0145	1.45
5	0.0375	0.75	0.055	1.1
10	0.024	0.24	0.022	0.22

The accuracy of the motion in the Y axis was also evaluated as shown in Figure 12. The robot was moved using the software at a certain distance and the actual distance of the motion was recorded using the digital caliper. Motion steps of 1 mm, 5 mm and 10 mm were evaluated. Table 3 lists the actual measured distance at motion steps of 1 mm, 5 mm and 10 mm for the Y axis. Figure 13 shows the actual measured distance versus the intended distance for the Y axis forward motion and Figure 14 shows the actual measured distance versus the intended distance for the Y axis reverse motion.

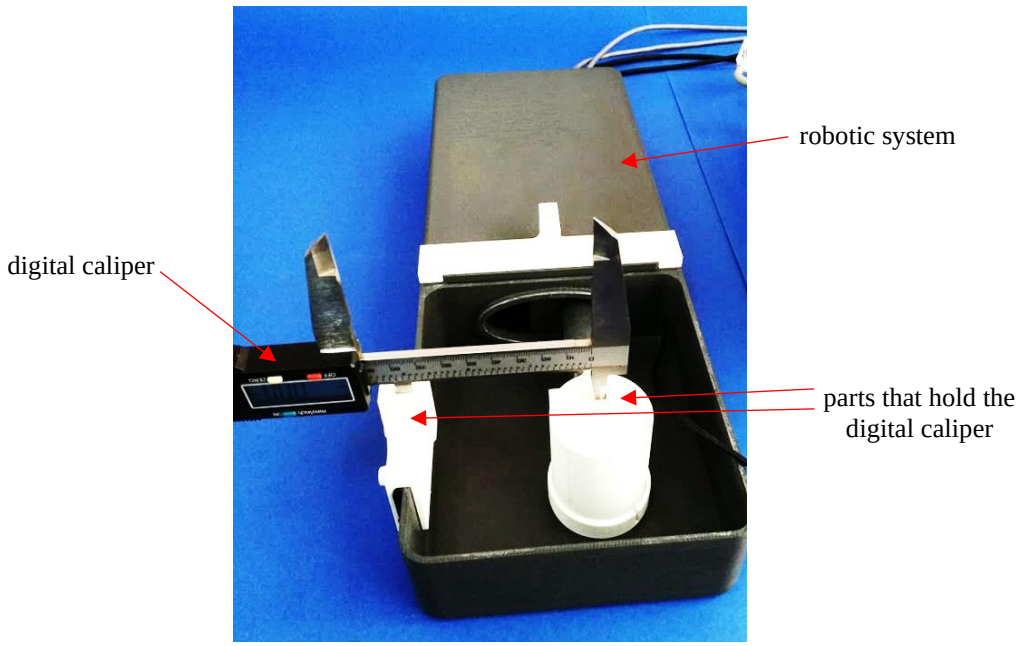

Figure 12: Evaluation of the motion of the robotic device in the Y axis.

Table 3: List of distance measurements taken at motion step of 1, 5 and 10 mm for the Y axis evaluation.

Intended distance (mm)	**1**		**5**		**10**	
Measurement number	**Distance moved forward (mm)**	**Distance moved reverse (mm)**	**Distance moved forward (mm)**	**Distance moved reverse (mm)**	**Distance moved forward (mm)**	**Distance moved reverse (mm)**
1	1.02	0.78	4.54	4.78	9.68	9.68
2	0.94	0.89	5.01	4.91	10.07	10.11
3	1.05	1.07	4.78	4.94	10.18	10.07
4	0.93	1.04	4.98	4.82	10.10	9.95
5	0.98	0.89	4.95	4.89	9.61	9.63
6	0.92	0.84	4.88	4.81	9.91	10.08
7	0.89	1.07	4.84	4.86	10.08	10.10
8	0.89	1.01	4.94	4.65	10.17	9.84
9	0.96	0.89	4.53	4.87	9.65	9.71
10	0.95	0.95	5.05	4.92	9.92	10.18
11	0.88	0.91	4.96	5.09	10.17	10.04
12	1.06	1.01	4.77	5.07	10.12	9.78
13	0.93	1.01	5.03	4.91	9.56	9.70
14	0.80	1.05	5.08	4.98	9.94	10.14
15	0.79	0.72	5.05	5.09	10.17	10.03
16	1.01	0.79	5.05	4.81	9.99	9.85
17	1.08	1.06	4.70	4.56	9.61	9.61
18	0.84	0.96	4.84	4.88	9.88	10.13
19	0.90	0.93	4.82	5.05	10.20	10.15
20	1.05	0.92	5.04	4.97	10.04	9.81
Average	**0.9435**	**0.9395**	**4.892**	**4.893**	**9.9525**	**9.9295**

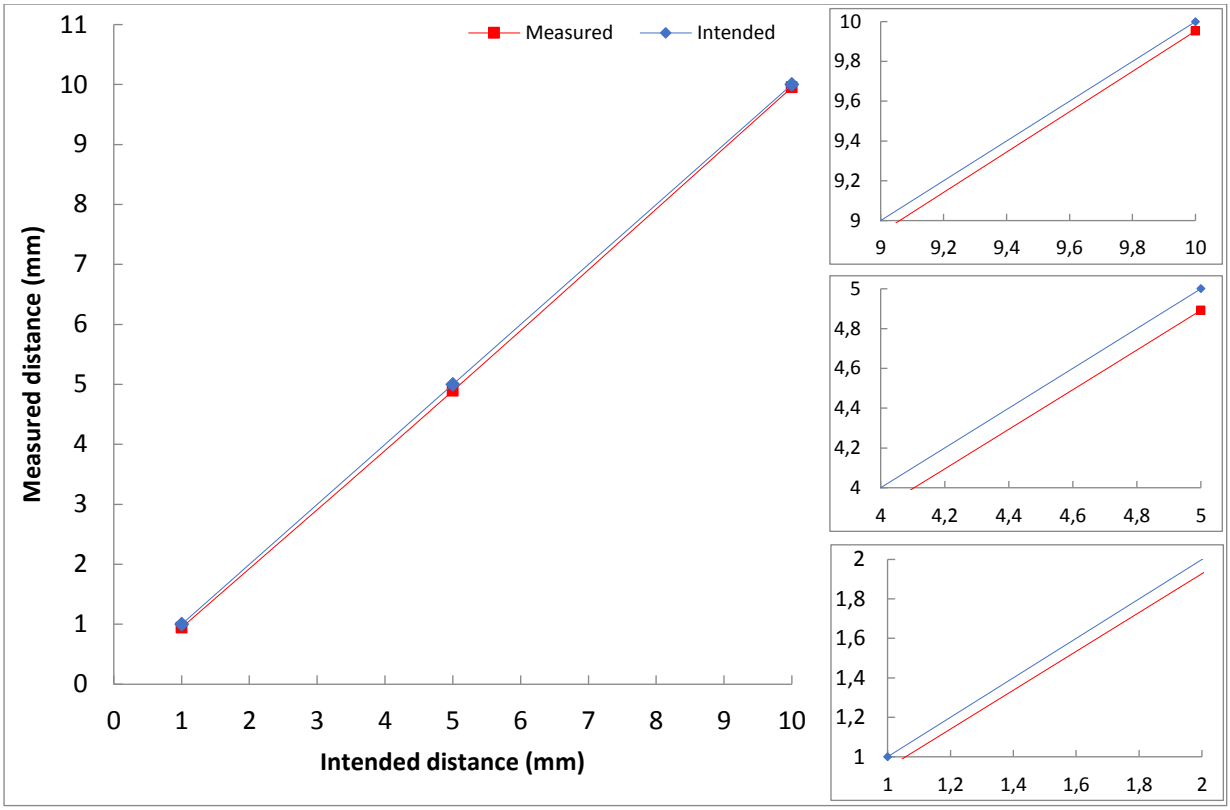

Figure 13: Measured distance versus intended distance for the Y axis forward motion (left) and zoomed areas of the graph (right).

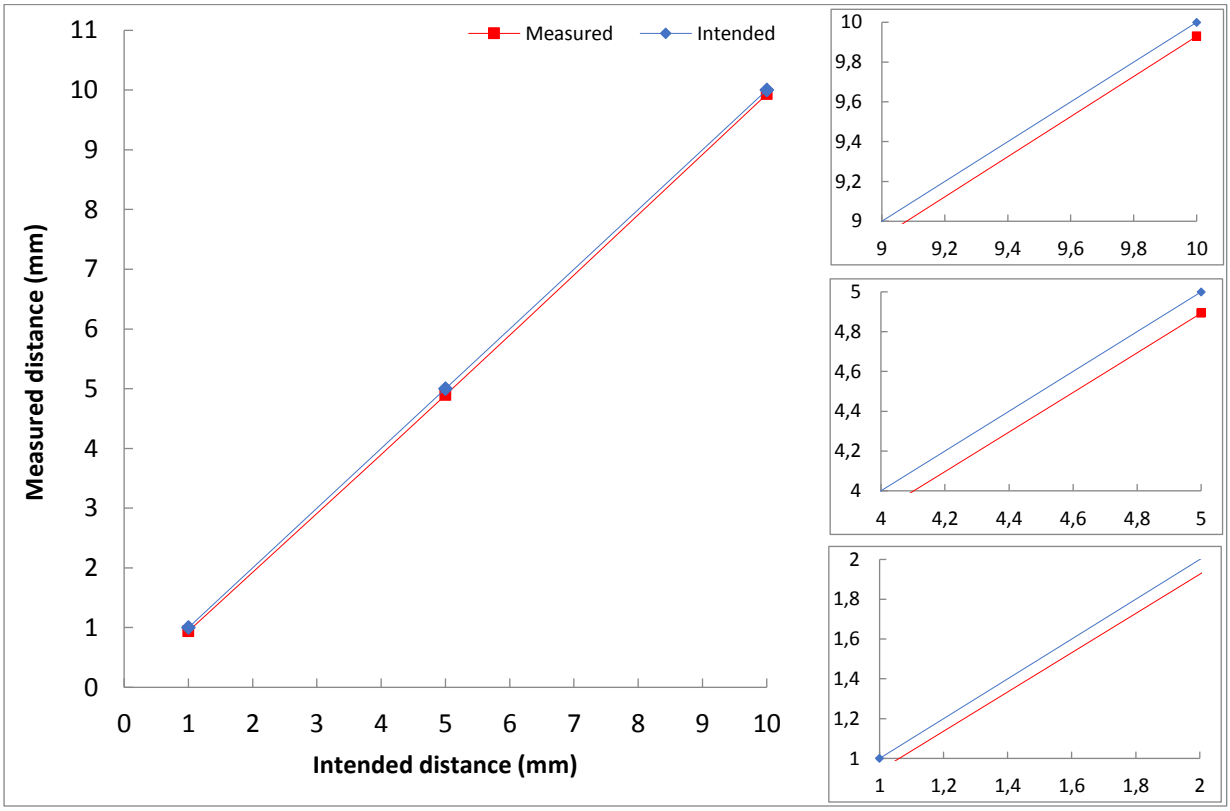

Figure 14: Measured distance versus intended distance for the Y axis reverse motion (left) and zoomed areas of the graph (right).

The error at each step movement of the robotic device was also estimated for the Y axis motion. Table 4 summarizes the error measured at motion steps of 1 mm, 5 mm and 10 mm for the Y axis forward and reverse directions.

Table 4: List of error estimated at different motion steps for the Y axis forward and reverse directions.

Step (mm)	Error-forward motion	Error-forward motion (%)	Error-reverse motion	Error-reverse motion (%)
1	0.0565	5.65	0.0605	6.05
5	0.108	2.16	0.107	2.14
10	0.0475	0.475	0.0705	0.705

The speed of the motion of the robotic device in both directions (X and Y axis) was estimated. Motions of different distances were performed and the time which the transducer holder took to travel that particular distance was calculated. The average speed of 5, 10, 20 and 40 mm distances was calculated. The speed at 1 mm distance was not included in the overall average speed since the time was less than a second and it was not so accurate. Tables 5 and 6 list the time needed for the transducer to cover various distances and the corresponding speed of motion for the X axis (forward and reverse direction) and the Y axis (forward and reverse direction) respectively.

Table 5: List of time needed for the transducer to cover different distances and speed of forward and reverse motion for the X axis.

Distance (mm)	**1**	**5**	**10**	**20**	**40**
Measurement number	**Time (s) for forward motion**				
1	0.84	3.1	5.34	11.28	29.69
2	0.75	2.65	5.13	11.41	34.16
3	0.78	2.56	5.25	12.85	35.53
4	0.81	2.6	5.38	12.88	39
Average Time	0.795	2.7275	5.275	12.105	34.595
Speed (mm/s)	1.26	1.83	1.89	1.65	1.16
Speed of forward motion (average all)	1.56 mm/s				
Measurement number	**Time (s) for reverse motion**				
1	0.81	2.56	4.87	10.5	24.32
2	0.75	2.41	4.94	11.47	26.87
3	0.75	2.57	5.22	11.25	29.82
4	0.69	2.62	5.69	12.22	37
Average Time	0.75	2.54	5.18	11.36	29.5025
Speed (mm/s)	1.33	1.97	1.93	1.76	1.36
Speed of reverse motion (average all)	1.67 mm/s				

Table 6: List of time needed for transducer to cover different distances and speed of forward and reverse motion for the Y axis.

Distance (mm)	**1**	**5**	**10**	**20**	**40**
Measurement number	**Time (s) for forward motion**				
1	0.88	1.53	3.31	6	10.75
2	0.71	1.43	3.06	5.88	10.71
3	0.63	1.47	3	6.25	11.13
4	0.53	1.53	3.03	5.94	11.63
Average Time	0.6875	1.49	3.1	6.0175	11.055
Speed (mm/s)	1.45	3.36	3.23	3.32	3.62
Speed of forward motion (average all)	3 mm/s				
Measurement number	**Time (s) for reverse motion**				
1	0.66	1.59	3.06	5.97	10.28
2	0.5	1.5	2.97	5.63	10.75
3	0.54	1.47	3	6.04	11.16
4	0.56	1.4	3.03	5.97	11.63
Average Time	0.565	1.49	3.015	5.9025	10.955
Speed (mm/s)	1.77	3.36	3.32	3.39	3.65
Speed of reverse motion (average all)	3.1 mm/s				

Conclusions

The accuracy of the motion of the two DOF robotic system was evaluated. The accuracy of the motion was tested at step movements of 1 mm, 5 mm and 10 mm using digital calipers with a special designed set-up.

The error at each step movement of the robotic device was estimated for both the X and Y axis (forward and reverse) motion. For the X axis motion, at step movement of 1 mm the error of the forward motion was greater than the reverse motion and it was the biggest error of all the moving steps of the X axis. At step movement of 5 mm the error of the forward motion was less than the reverse motion while at step movement of 10 mm the error between the forward and reverse direction was almost the same and was very low. On the other hand, for the Y axis motion at step movement of 1 mm the error of the forward motion was about the same as the reverse motion and it was accounted for around 6 %. The error of step movement of 5 mm was about one third of the error of 1 mm step motion (2 %) and there was no difference between the forward and reverse percentage error. The percentage error for 10 mm movement step was almost zero with no significant difference between the forward and reverse motion direction. It is concluded that the error of the motion of the robotic device decreases at larger distance steps.

Moreover, the speed motion of the robotic device in both axes and directions (forward and reverse) was also calculated. There was no significant difference between the speed motion in the forward and reverse direction. The speed of the robotic device in the Y axis was about double than the speed in the X axis. A possible reason for this difference in speed of movement between the 2 axes is the corresponding drivers (D6030, Shinsei Corporation) of the Shinsei motors. Motion speed depends mainly on the drivers and each driver can control the motors at different speeds. However, the motion of the motors and therefore the distance movement of the axes is not affected by the speed setting parameter of the drivers.

Therefore, for the 1 mm motion in the X-axis, the maximum error was 21 μm (forward direction). For 5 mm the maximum error was 37 μm for the same axis. For the Y-axis the maximum error was 56 μm for 1 mm step and 108 μm for 5 m step. The speed for the X-axis is about 1.56 mm/s for forward and for the Y-axis 3 mm/s in forward direction.