Project Acronym:

MRBREASTBIO (CONCEPT/0521/0040)

MRI breast robotic system for biopsy

Deliverable number: 5.2

Title: Evaluation of the accuracy of motion of the robotic system

Prepared by:

Anastasia Antoniou (CUT)
Christakis Damianou (CUT)

Date: 31/10/2022

Co-funded by the European Union

Republic of Cyprus

RESEARCH & INNOVATION FOUNDATION

Contents

Executive summary

This deliverable describes the procedure that has been followed to evaluate the motion accuracy of the MRBREASTBIO robotic device. The evaluation was performed using a digital caliper that was mounted on 3D-printed parts that were stably connected to the robotic system. The movement speeds of the positioning device have been estimated as well. To estimate the speed in all axes and directions, a digital stopwatch was used. The desired motion distances were commanded through a special software, which is connected to the electronic driving system, to which the robotic system's motors and encoders are plugged. The special software and the electronic driving system are also described.

The accuracy of the robotic system has been investigated at bidirectional step movements of 1.0 mm, 5.0 mm, 10.0 mm and 40.0 mm in both motion axis. The same step movements have been used to estimate the vertical and horizontal speeds in directions.

Introduction

Figure 1 shows the MRBREASTBIO robotic system and Figure 2 shows the respective CAD drawing. The MRBREASTBIO device is an MR compatible positioning device of two degrees of freedom (DOF) which performs a breast biopsy procedure under MRI-guidance. The developed robotic system includes MR compatible components and parts.

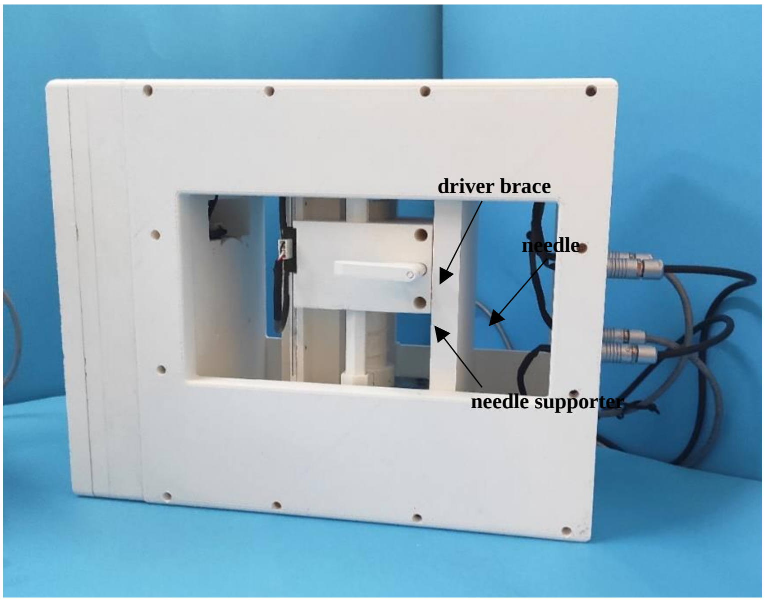

Figure 1: MRBREASTBIO robotic device with biopsy needle.

The robotic system consists of two stages of motion that are able to produce individually a linear motion. These stages of motion are the X-stage and the Y-stage. The X-stage provides a bidirectional motion along the X-axis to move the robotic system horizontally. The Y-stage produces a vertical bidirectional motion along the Y-axis.

Figure 2: CAD drawings of MRBREASTBIO robotic device.

Both of these motions are provided through MR-compatible motors. The mechanical part of the positioning device converts the rotational movement of the motors into the two-dimensional linear motion of the brace part inside which a biopsy needle is inserted. The horizontal and vertical displacements are detected by two MR-compatible encoders. These encoders are appropriately positioned to detect the robotic system's movement along both axes (X and Y) throughout its entire operation, thus ensuring the required motion accuracy.

Evaluation of the accuracy

Description of the evaluation procedure

The current experiment aimed to evaluate the accuracy of motion of the 2 DOF positioning device named as MRBREASTBIO. Since the device produces two individual motions, the evaluation procedure is divided into two main parts referred to as “Y-stage evaluation” and “X-stage evaluation”.

Specifically, the Y-stage evaluation was performed to examine the accuracy of the robotic system’s Y-stage motion. As it has been described before, the Y-stage motion provides vertical movement (along Y-axis). Moving on, the X-stage evaluation was done to define the accuracy of the X-stage which produces the horizontal motion of the robotic system (along X-axis).

The process that has been followed to evaluate the robotic system’s accuracy is briefly described below. Figure 3 shows the experimental setup that has been developed to evaluate the motion accuracy of the MRBREASTBIO robotic device.

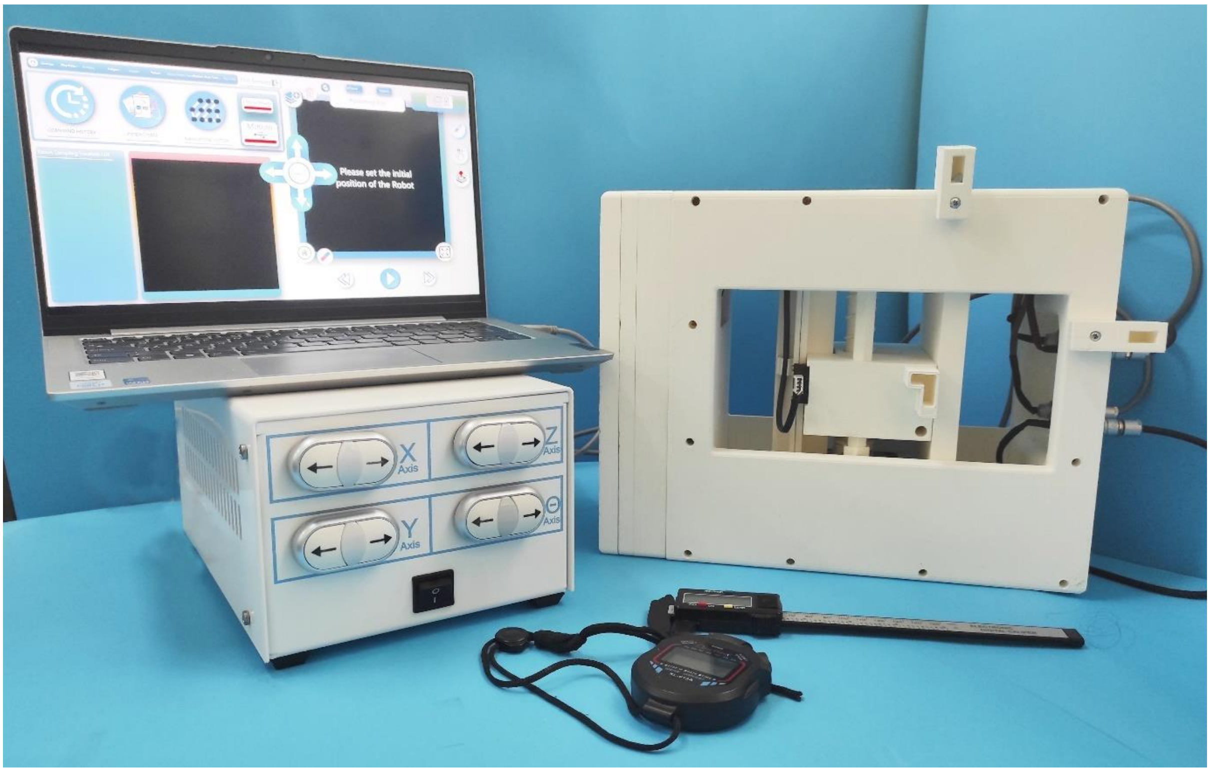

Figure 3: Experimental set-up for motion accuracy assessment.

An electronic driving system and a special software were used to PC-control the robotic system. The software, through its connection with the electronic driving system to which the positioning device is connected, produces the desired motion of both Y-stage and X-stage, individually. During the estimation process, the vector command of the software was used to force the robotic system to move by several desired distances. At the same time, a digital digimatic caliper (Series500 0-150mm, Mitutoyo,Illinois, USA) that is shown in Figure 4, was used to measure the actual distance between the beginning and the final point of the movement.

A comparison between desired and actual motion distances was done to examine the accuracy of the MRBREATSBIO robotic device.

Figure 4: The digital digimatic caliper that was used to measure the actual distance.

Software

The special software shown in Figure 5 has been developed to create an ideal communication environment between the user (doctor) and the robotic system. The software is directly connected to the electronic driving system and to the MRI-scanner.

The MRI scanner, to which the robotic system is inserted to execute a breast biopsy procedure, is used to acquire the desired MRI images. The MRI-images are used by the developed software to estimate the motion that the robotic system should undertake to target the tumor. Specifically, an MRI-image is used to detect the position of the tumor, whilst a second one is used to detect the initial position of the robotic device. The initial position of the robotic system is detected using a water-filled syringe that is placed in the same position as the biopsy needle. These images are provided to the software as inputs to calculate the required displacement of the robotic system.

By the time the estimation of the robotic system's required displacement is completed, the software is able to send the appropriate commands that include the desired vertical and horizontal distances to the electronic driving system.

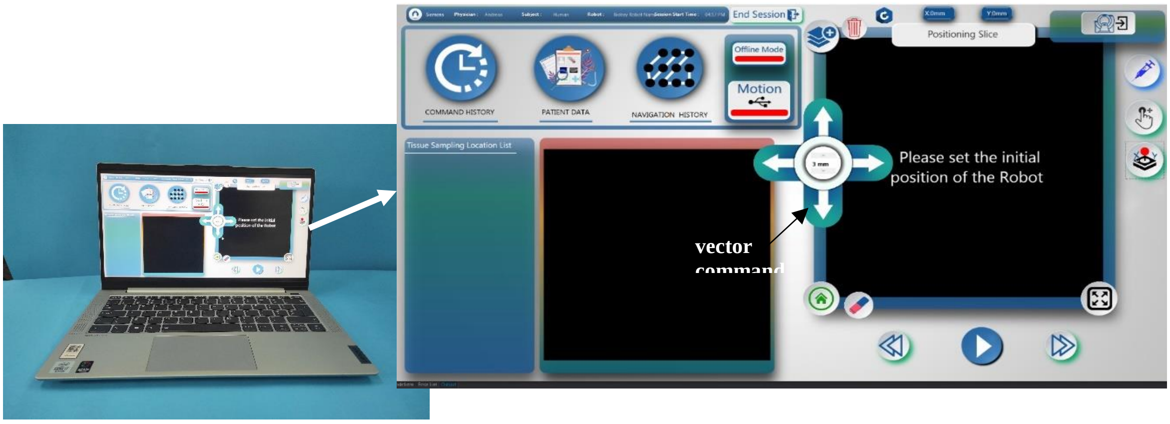

Figure 5: The special software running on the lab's laptop.

Notably, the vector command that is shown in Figure 5 is used to manually move the robotic system if necessary.

Electronic driving system

The electronic driving system that is used throughout the entire procedure to actuate the desired motions is shown in Figure 6. Figures 6B and 6C show the main parts of the electronic system. These parts are the connector plugs of the motors and encoders, the power supply, a driver controller and an Arduino board (microcontroller). All of the abovementioned parts are enclosed in a constructed housing, as the Figure 6A shows.

The motors and the encoders used to produce and monitor the motion of the MRBREASTBIO device are connected to the microcontroller of the electronic driving system through the respective connector plugs. An Arduino board (microcontroller) is connected to both the driver controller and PC, to which the special software is running. The Arduino microcontroller receives from the software the appropriate commands to provide the desired motion to the robotic system. The motors' operation is controlled by the Arduino board, which receives encoders' signals to detect the robotic system's displacement.

Figure 6: (A)The electronic driving system enclosed in the constructed housing, (B) The electronic driving system without housing. (C) Top view of the electronic driving system without the housing.

Evaluation of Y-stage motion’s accuracy

To evaluate the Y-stage motion, additional parts were developed. These parts, whose CAD drawings are shown in Figure 7, have been designed using the Inventor Software® and constructed by a 3D printer (F270, Stratasys, Minnesota, USA). The Polylactic acid (PLA) plastic was used to fabricate the robotic parts.

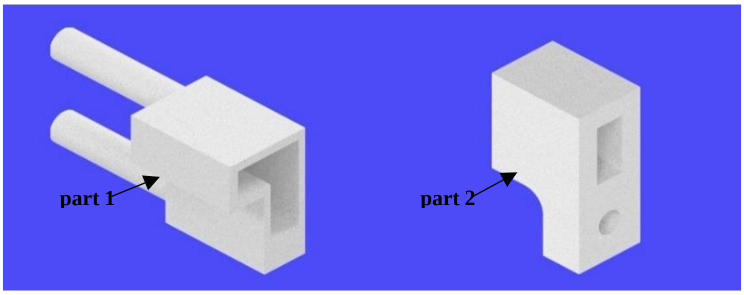

Figure 7: CAD drawings of the 3D-printed parts used to support the digital caliper throughout the evaluation of the Y-stage.

Figure 8 shows the way the new parts 1 and 2 are stably positioned on the MRBREASTBIO device and the way the digital caliper was placed.

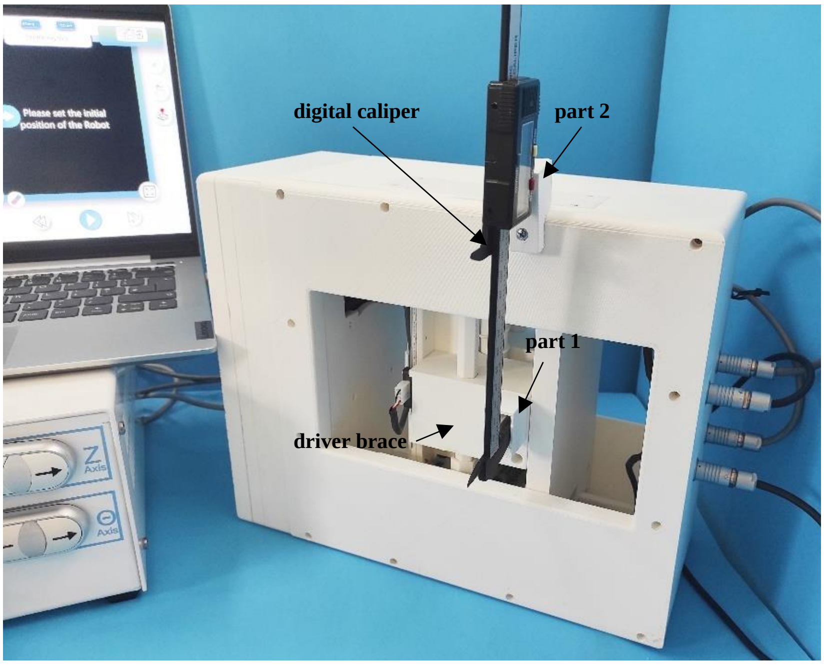

Figure 8: The robotic system with the 3D-printed parts and the digital caliper that have been used for the evaluation of the Y-stage.

The described software was set to move the robotic system by 4 different desired distances several times. Due to the constructed spaces on the Y-stage’s driver brace the doctor can choose the most appropriate space to which the biopsy needle will be inserted. As it has been described in Deliverable 3.1 there are 3 vertical offset spaces. Therefore, to evaluate the Y-stage along its entire range of motion, all the 3 positions have been considered.

The 4 different desired distances that the robotic system has been forced to move are 1.0 mm, 5.0 mm, 10.0 mm and 40.0 mm. During the evaluation procedure, each of the desired movements was repeated 7 times for each potential position in both upwards and downwards directions.

Table 1: List of the measured (actual) distances taken at several motion steps for the evaluation of the Y-stage.

Intended distance (mm)	**1.0**		**5.0**		**10.0**		**40.0**	
Measurement (n)	Distance moved upwards (mm)	Distance moved downwards (mm)	Distance moved upwards (mm)	Distance moved downwards (mm)	Distance moved upwards (mm)	Distance moved downwards (mm)	Distance moved upwards (mm)	Distance moved downwards (mm)
LOWER POSITION								
1	0.9	1.0	5.0	5.0	9.9	10.0	39.9	39.9
2	1.0	0.9	4.9	5.0	10.0	10.0	39.9	40.1
3	0.9	1.0	4.9	4.9	10.0	9.9	40.1	39.9
4	1.0	0.9	5.0	5.0	10.0	9.9	40.1	40.0
5	1.0	0.9	4.9	5.0	9.9	10.1	39.9	39.9
6	1.0	1.0	4.9	4.9	9.9	10.0	40.1	40.0
7	1.0	1.0	5.0	5.0	10.0	10.1	40.0	40.0
MIDDLE POSITION								
8	0.9	0.8	5.1	4.9	9.9	9.9	39.9	39.8
9	1.0	1.0	5.0	4.9	10.0	10.0	39.9	39.9
10	1.1	1.0	4.9	5.1	10.1	9.9	39.9	39.9
11	1.0	1.0	5.0	5.0	10.0	9.9	40.0	39.8
12	1.0	1.1	5.0	5.0	10.0	10.0	39.9	39.9
13	1.0	1.0	5.0	5.0	10.0	9.9	39.9	40.0
14	1.0	1.0	5.0	4.9	9.9	9.9	40.0	40.0
UPPER POSITION								
15	1.0	0.9	4.9	4.9	10.0	9.9	39.9	39.9
16	1.0	1.0	4.9	5.0	9.9	10.0	40.0	40.0
17	0.9	0.9	5.0	4.9	10.0	10.0	40.0	39.9
18	1.0	1.0	4.9	5.0	10.0	9.9	39.9	39.9
19	0.9	1.1	5.0	5.0	10.1	9.9	40.0	39.8
20	1.0	1.0	5.0	4.9	10.0	10.0	39.9	40.0
21	0.9	0.9	4.9	5.0	10.0	10.1	40.0	40.0

Mean value (mm)	**1.0**	**1.0**	**5.0**	**5.0**	**10.0**	**10.0**	**40.0**	**39.9**
Standard deviation (mm)	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**

Table 1 lists the actual distances that the Y-stage covered for each respective desired motion step. For each motion distance, the measurements are presented in two columns. The left column lists the measurements of the upward movement of the robotic system, whilst the right one lists the ones for the downward movement. The table is also divided in 3 sections. Each of these sections represents the results of the evaluation for each potential position of the needle supporter.

The mean values of the actual distances and the standard deviations have been calculated and presented in the last rows of the Table 1. Figure 9 shows the mean values of the measured (actual) distances plotted against the desired (intended) ones.

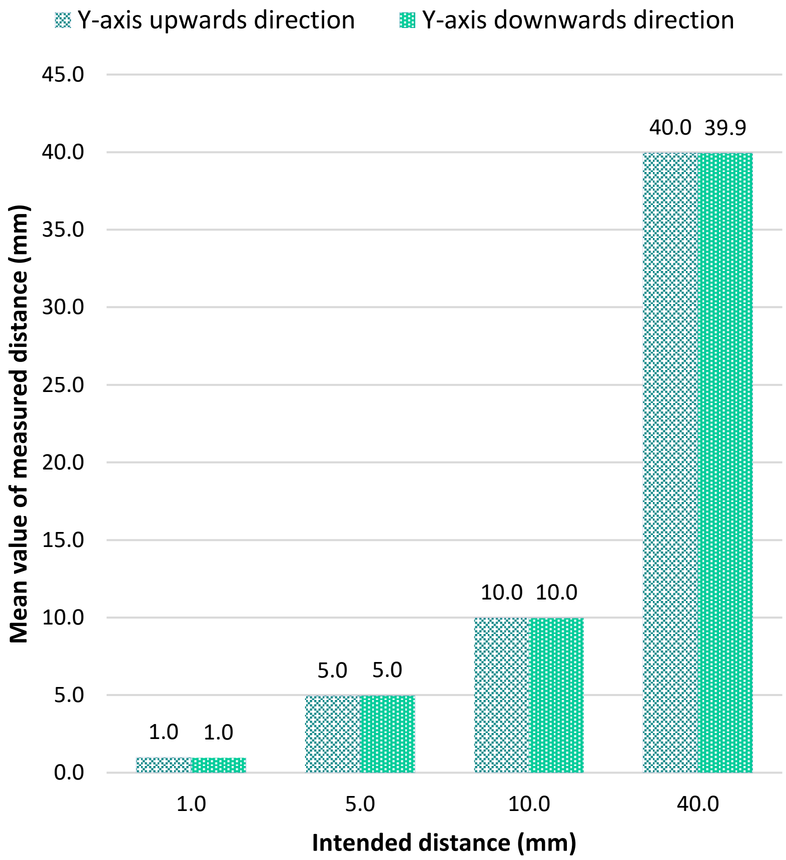

Figure 9: Mean values of the measured distances versus the respective Intended distances of all the desired motion steps in both directions of the Y-axis.

Figures 10 to 13 show the graphs that have been developed during the evaluation of the Y-stage. Each graph presents the measured displacement versus measurement number at each motion step in both vertical directions. Notably, the graphs are divided into 3 sections to clarify the position which is under examination. Also, for comparison reasons the desired distance, consider as intended distance, is also presented on the graph of each accuracy evaluation procedure.

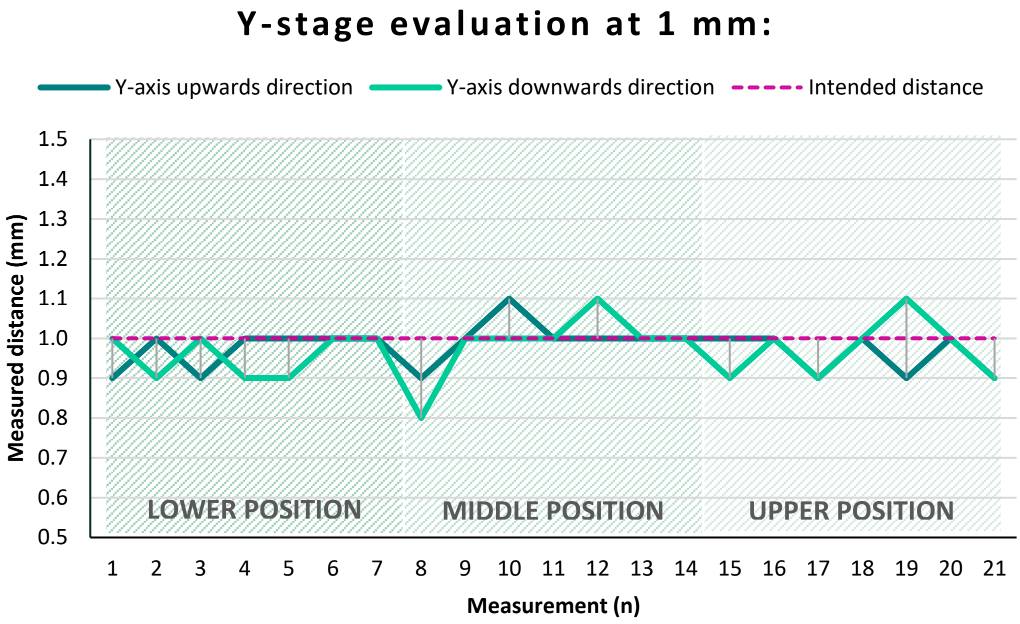

Figure 10: Measured distances of all the measurements taken bidirectionally to assess the 1.0 mm motion step along the Y-axis.

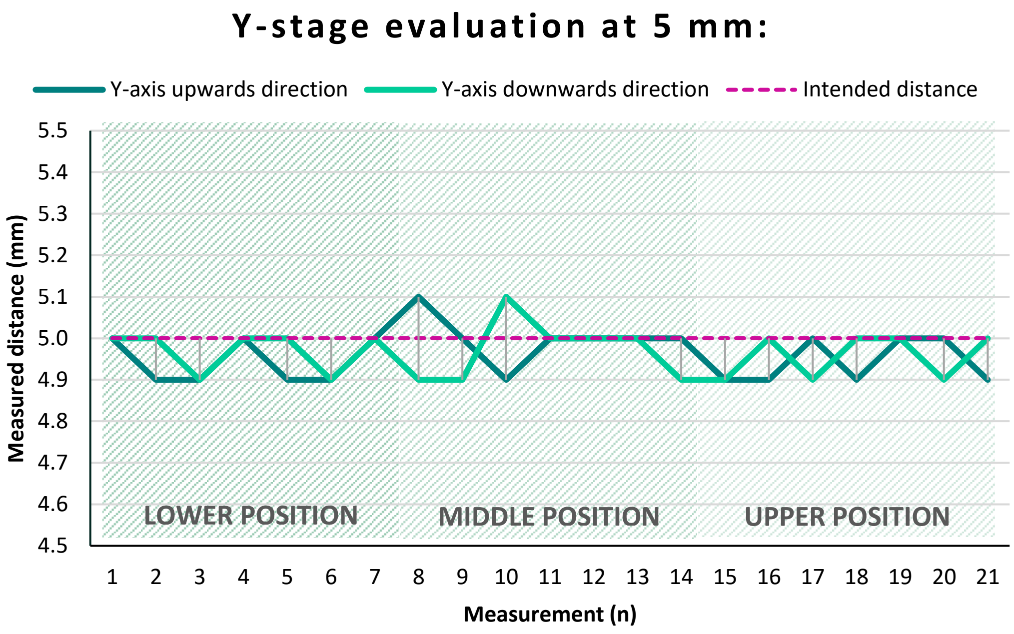

Figure 11:Measured distances of all the measurements taken bidirectionally to assessor the 5.0 mm motion step along the Y-axis.

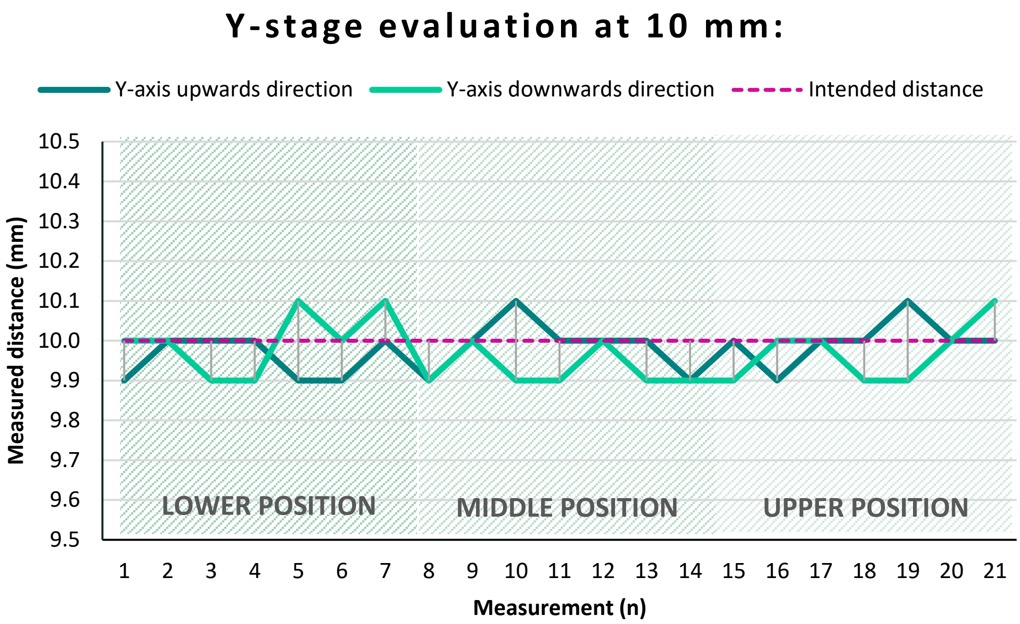

Figure 12: Measured distances of all the measurements taken bidirectionally to assess the 10.0 mm motion step along the Y-axis.

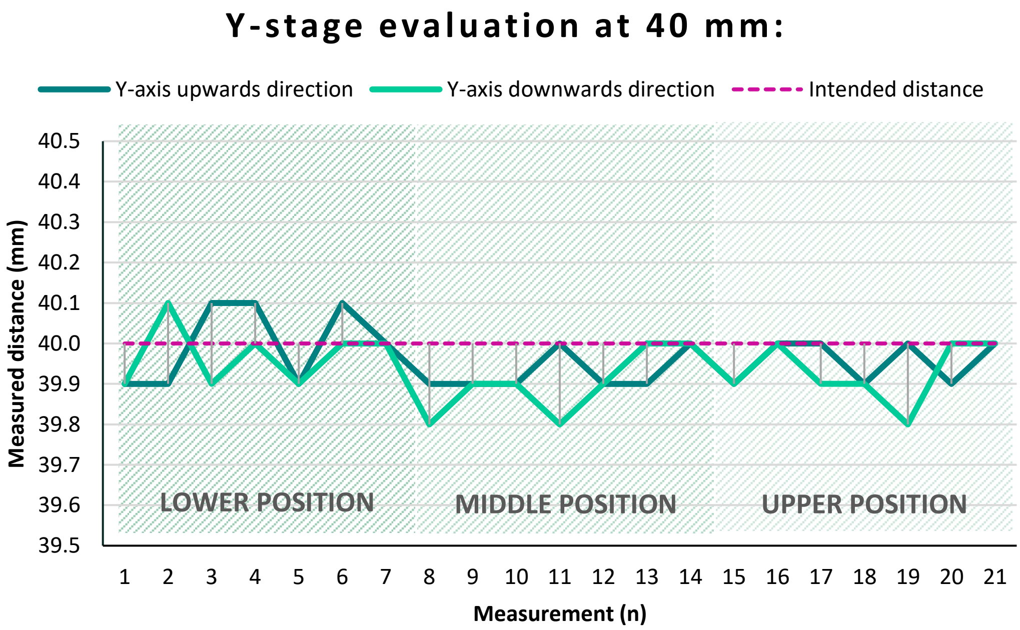

Figure 13: Measured distances of all the measurements taken bidirectionally to assess the 40.0 mm motion step along the Y-axis.

Moving on, the error between the mean values of the actual distances and the desired ones have has been calculated. Table 2 lists the error estimations for all the desired motions that the robotic system undertaken throughout the entire evaluation procedure of its accuracy. As it is presented the error has been separately calculated for the upward and downward directions.

Table 2: List of error estimated at all the desired motions executed by the Y-stage.

Intended distance (mm)	Upward direction		Downward direction	
	Error (**mm**)	Error (**%**)	Error (**mm**)	Error (**%**)
1	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000
40	0.000	0.000	-0.003	-0.300

Evaluation of X-stage motion's accuracy

After the evaluation of the Y-stage motion's accuracy was completed, the X-stage motion's accuracy was also evaluated. To evaluate the X-stage motion's accuracy, the parts 1 and 3 were developed. Both parts that are shown in Figure 14 have been designed using the Inventor Software® and constructed by a 3D printer (F270, Stratasys, Minnesota, USA) that produces PLA plastic components.

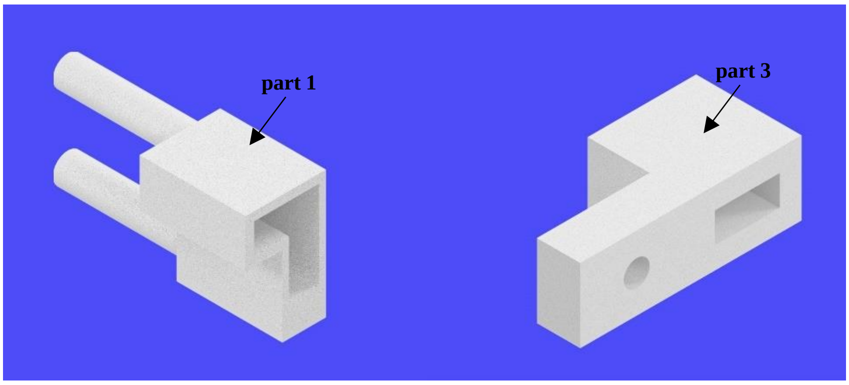

Figure 14: CAD drawings of the 3D-printed parts used to support the digital caliper throughout the evaluation of the X-stage.

Figure 15 shows the integration of the parts 1 and 3 on the MRBREASTBIO robotic device, to which they are rigidly connected. The way the digital caliper as the detection tool is inserted in these parts is also presented.

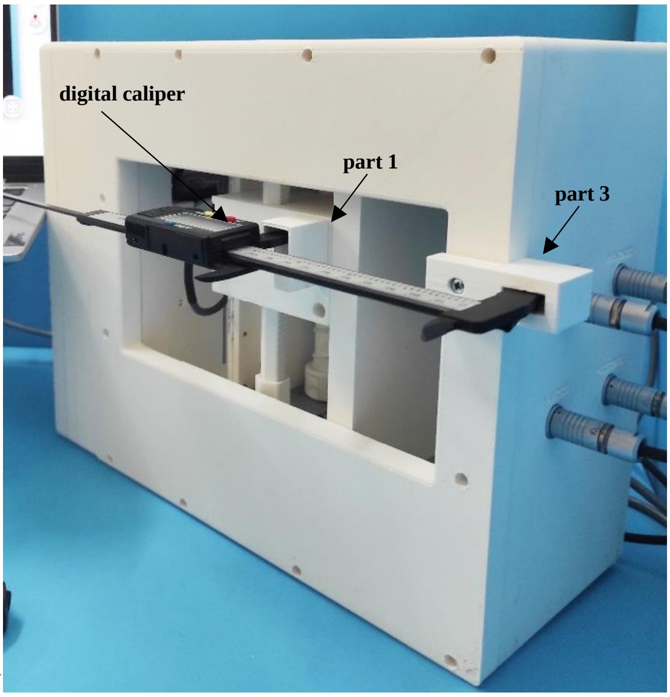

Figure 15: The robotic system with the 3D-printed parts and the digital caliper that have been used for the evaluation of the X-stage.

Following a similar procedure as previously, the already described software was used to move the system in several desired distances on both axes. Characteristically, 4 different desired displacements have been chosen to examine the X-stage's accuracy. These 4 displacements are; 1.0 mm, 5.0 mm, 10.0 mm and 40.0 mm. It is essential to clarify that all of the displacements have been performed in both right and left directions. As the Table 3 presents, both directions were separately examined, and the corresponding results are listed. For each desired displacement there are two columns, each of them representing a different direction. The left column lists the actual distances measured in the right direction, whilst the right column lists the ones measured for the left direction movement.

The last two rows of Table 3 present the calculated mean values and standard deviations of all the measurements done throughout the entire procedure. Figure 16 shows the mean values of the measured (actual) distances in correspond with the desired (intended) ones.

Table 3: List of the measured (actual) distances taken at several motion steps for the evaluation of the X-stage.

Intended distance (mm)	**1.0**		**5.0**		**10.0**		**40.0**	
Measurement (n)	Distance moved right (mm)	Distance moved left (mm)	Distance moved right (mm)	Distance moved left (mm)	Distance moved right (mm)	Distance moved left (mm)	Distance moved right (mm)	Distance moved left (mm)
1	0.9	0.9	5.0	5.0	10.0	10.1	39.9	40.0
2	0.9	1.0	5.1	5.1	10.0	10.1	40.1	40.0
3	0.9	1.0	5.0	5.0	9.9	10.0	39.9	39.8
4	1.0	0.9	5.0	5.1	10.0	10.0	39.9	39.9
5	1.0	1.0	4.9	5.0	9.9	10.0	40.0	39.9
6	1.0	1.1	5.1	5.1	10.1	10.1	39.9	40.1
7	0.9	1.0	5.0	5.0	10.0	10.1	40.0	40.1
8	0.9	1.0	5.0	5.0	9.9	10.0	39.8	40.0
9	1.0	1.0	5.0	5.1	10.0	10.0	39.9	40.0
10	1.0	1.0	5.0	5.0	9.9	10.0	40.0	40.1
11	1.1	1.1	5.0	5.0	10.1	10.1	40.1	40.1
12	1.0	1.0	5.1	5.1	10.0	10.1	40.0	40.1
13	1.0	1.0	5.1	5.0	10.0	10.1	39.8	40.1
14	1.0	0.9	5.0	5.0	10.0	10.0	40.0	40.0
15	1.0	1.0	5.0	5.1	9.9	10.0	39.8	40.0
16	1.0	0.9	5.0	5.0	10.0	10.0	40.1	40.2
17	1.0	1.0	5.0	5.0	10.0	10.1	39.9	40.1
18	1.0	1.0	5.0	5.0	10.0	10.1	39.8	40.1
19	1.0	1.0	5.0	5.1	10.1	10.0	39.9	40.1
20	1.0	1.1	5.0	5.0	10.0	10.1	39.9	40.1
Mean value (mm)	**1.0**	**1.0**	**5.0**	**5.0**	**10.0**	**10.1**	**39.9**	**40.0**
Standard deviation (mm)	**0.1**	**0.1**	**0.0**	**0.0**	**0.1**	**0.1**	**0.1**	**0.1**

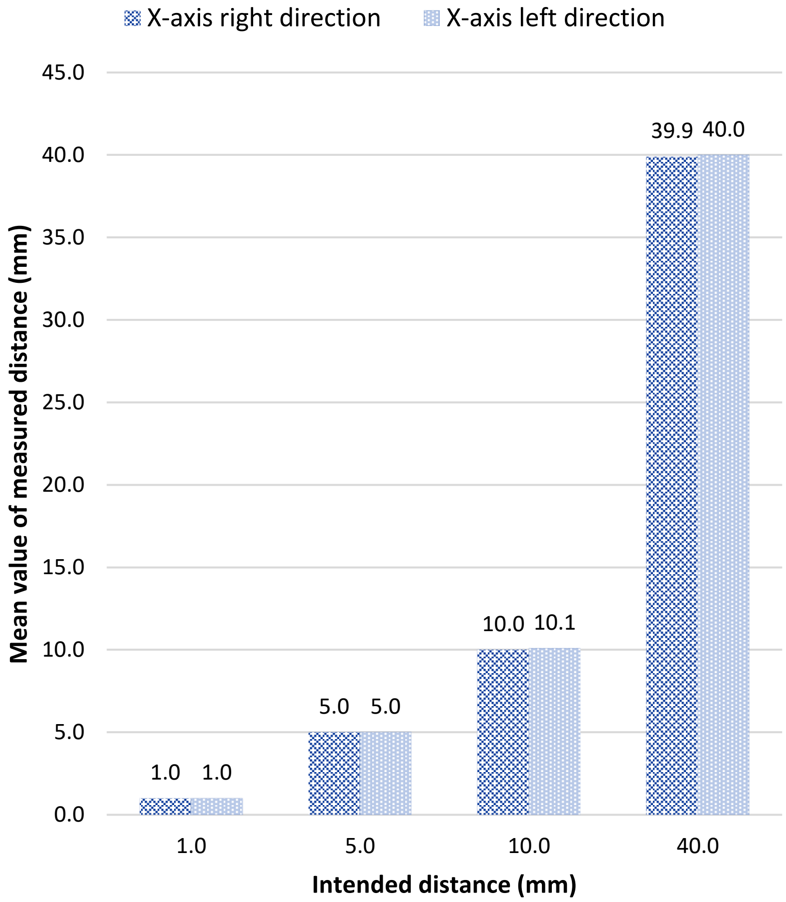

Figure 16: Mean values of the measured distances versus the respective intended distances for all the desired motion steps in both directions of the X-axis.

Moving on, Figures 17 to 20 show the graphs that have been created from the data of Table 3 to visually present the measured results of the X-stage's evaluation procedure. Each graph represents the results of the evaluation of the same desired distance for both directions. The desired (intended) distance is also presented for comparison reasons.

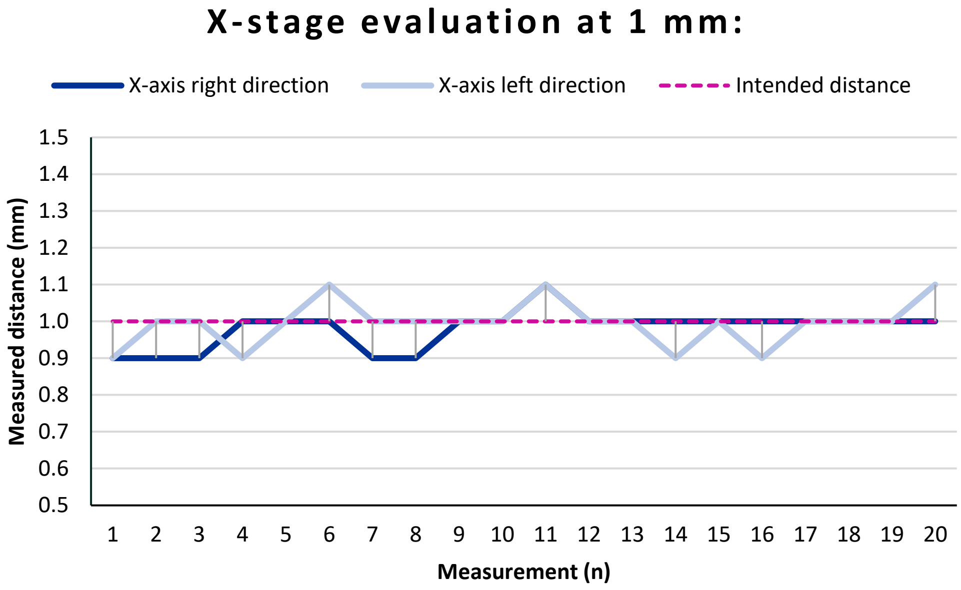

Figure 17: Measured distances of all the measurements taken bidirectionally to assess the 1.0 mm motion step along the X-axis.

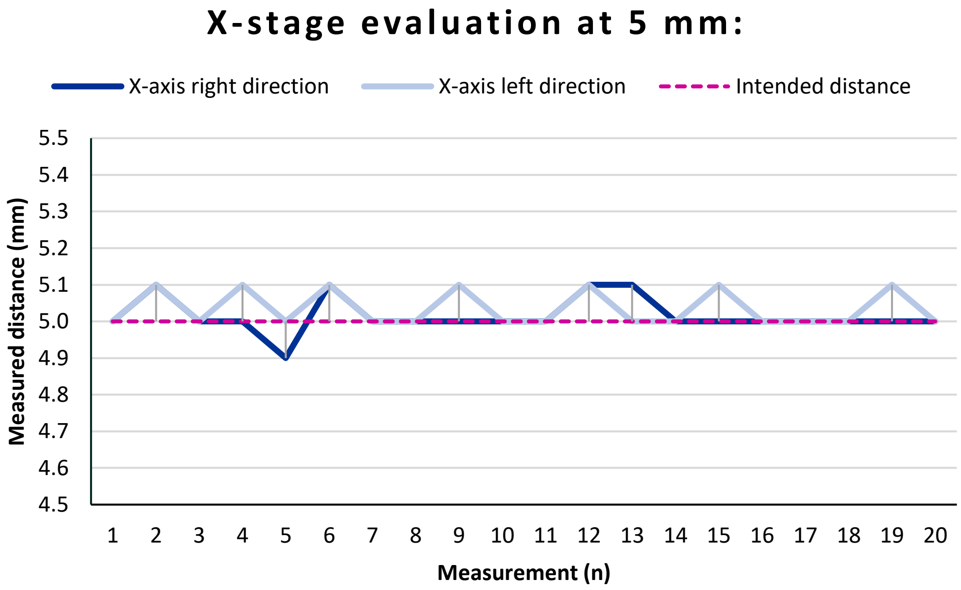

Figure 18: Measured distances of all the measurements taken bidirectionally to assess the 5.0 mm motion step along the X-axis.

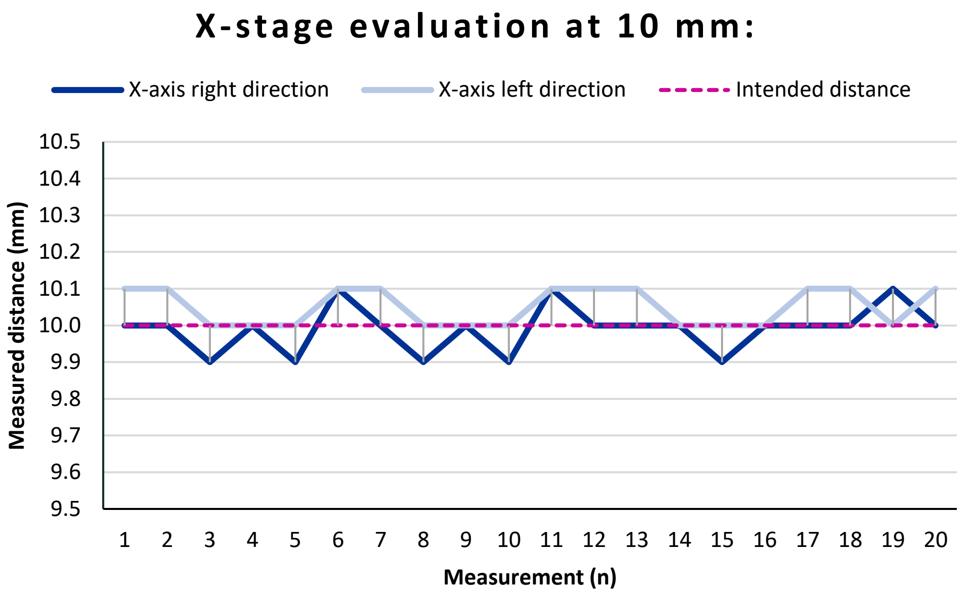

Figure 19:Measured distances of all the measurements taken bidirectionally to assess the 10.0 mm motion step along the X-axis.

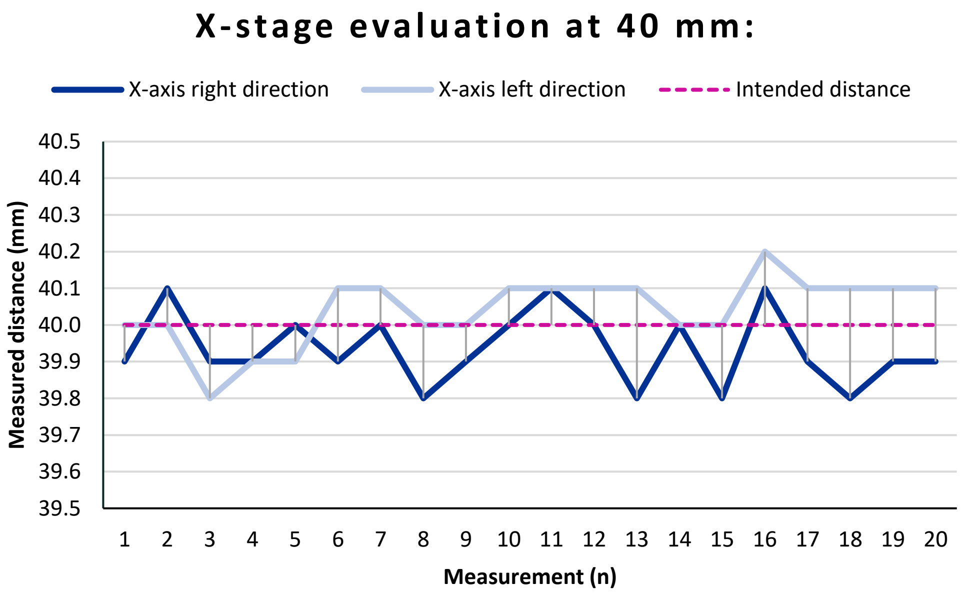

Figure 20: Measured distances of all the measurements taken bidirectionally to assess the 40.0 mm motion step along the X-axis.

Table 4: List of error estimated at all the desired motion steps executed by the X-stage.

Intended distance (mm)	Right dimension		Left dimension	
	Error (mm)	Error (%)	Error (mm)	Error (%)
1.0	0.000	0.00	0.000	0.00
5.0	0.000	0.00	0.000	0.00
10.0	0.000	0.00	0.010	1.00
40.0	-0.003	-0.30	0.000	0.00

Speed estimation

Description of the estimation procedure

In this section of the current deliverable the results regarding the speed with which the MRBREASTBIO robotic system is moving are presented. The speed has been estimated for both of its individual movements (along X and Y axis).

Specifically, the Y-stage has been examined to estimate the so called "vertical speed" with which the robotic system moves along the Y-axis. Similarly, the X-stage has been investigated to calculate the so called "horizontal speed" with which the robotic system moves along the X-axis.

It is essential to note that the estimation of the speed was based on the following speed definition

$$\vec{U} = \frac{\Delta\vec{x}}{\Delta t},$$

where U represents the calculated speed, Δx is the distance that the under-examination body covers in a time period equal to Δt. For the current estimation procedure, all the values were considered as absolute values to calculate the numerical value of the speed.

The procedure that was followed to estimate the movement speeds will be briefly described below. The stopwatch that is shown in Figure 21 was used to count the time that the robotic system needed to execute the desired motion.

Figure 21: Stopwatch that was used to count the time the robotic system needed to complete the several desired motions.

The desired motion was provided to the robotic system through its interconnection with the electronic driving system. As it has been detailly described in the section “Evaluation of the accuracy”, the electronic driving system is also connected to a special software. Due to this connection, the special software is able to move the robotic system in the direction and distance that the user desires. As the robotic system moves and the stopwatch counts, a digital caliper (same as previously) measures the actual displacement to ensure the robot’s motion accuracy. The measurements of the time period that the robotic system needed to complete the desired movement and the corresponding desired distances have been considered to estimate the vertical and horizontal speed, with which the MRBREASBIO device is moving.

Estimation of Y-stage motion speed

Figure 22 shows the experimental set up that was developed to estimate the vertical speed of the Y-stage motion.

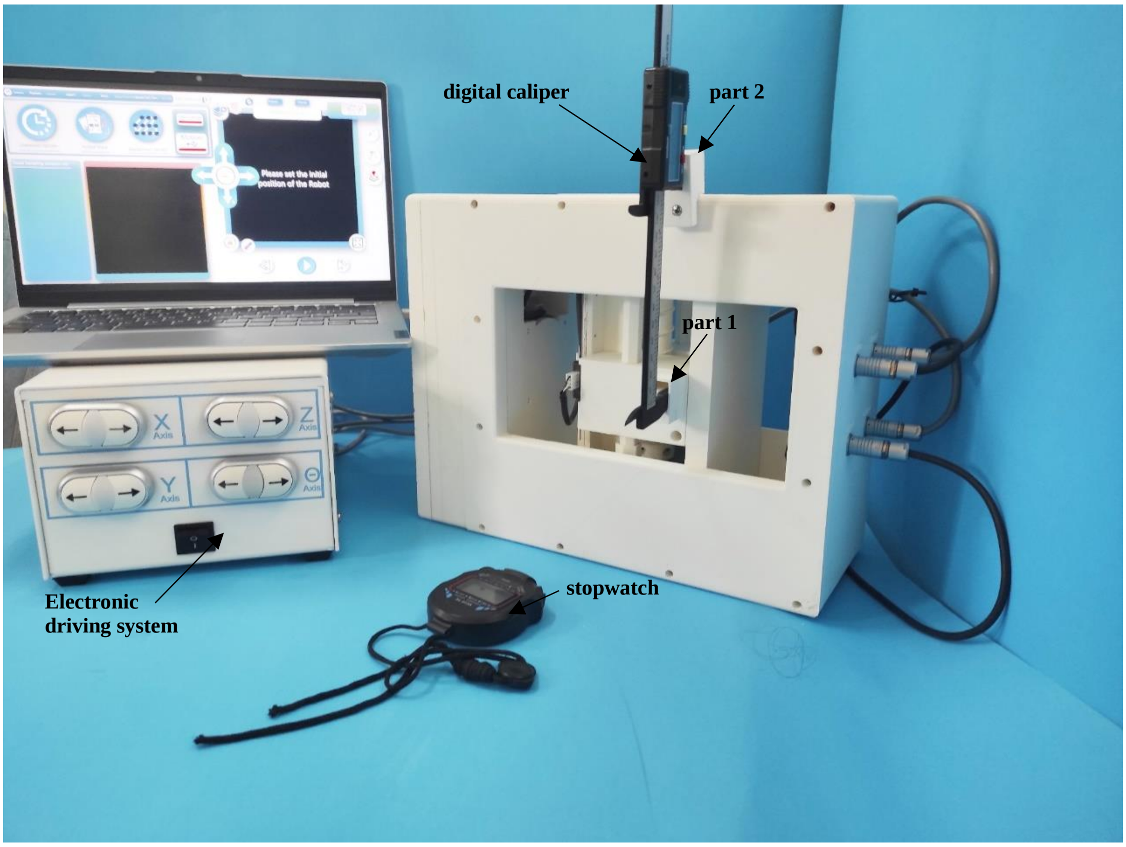

Figure 22:Experimental set up to estimate the speeds with which the robotic system moves bidirectionally along the Y-axis.

Except for the stopwatch, which was used to count the time period, two 3D printed parts and a digital caliper were used. These parts are the same parts that have been constructed and used to evaluate the accuracy of the Y-stage motion. The digital caliper was rigidly connected to the parts 1 and 2, as shown in Figure 22 to measure the displacement of the robotic system throughout its entire movement.

The special software described before was used to move the robotic system along the Y-axis. Between the beginning of the Y-stage motion and the time the user sends to the electronic driving system the desired motion's inputs (through the software's interface), there is a time period called as response time. This response time represents the time that the software and the electronic driving system need to send the desired motion commands to the robotic system. Thus, before the estimation procedure, the response time of the robotic system has been examined. The same inputs were sent to the robotic device several times and the measured response times as counted by the stopwatch are listed in Table 5.

Table 5: Response time of several measurements to estimate the response time of the Y-stage motion.

Measurement (n)	Response time (s)
1	1.00
2	1.01
3	1.05
4	1.01
5	1.02
Mean Response time value (s)	**1.02**

After the estimation of the response time, the procedure to estimate the movement speed was begun. The robotic system was forced to move by 4 different desired distances in both upward and downward directions. The 4 displacements are; 1.0 mm, 5.0 mm, 10.0 mm and 40.0 mm. Each of the movements has been repeatedly performed for several times. As the Table 6 presents, both directions were separately examined and the corresponding results are listed. Specifically, the table's left part presents the time that the Y-stage needed to complete its upward movement, whilst the right part lists the corresponding time periods for the Y-stage downward movement. The listed time values have been modified and they do not contain the response time.

The last three rows list the results of the measurement processing. The mean value of the time that the robotic system needed to perform the desired vertical movement has been calculated for each case. Then, the division of each desired distance with the respective mean time value was calculated to estimate the vertical speed of the robotic system at each tested distance (1.0, 5.0, 10.0, and 40.0 mm). The abovementioned measurement processing has been followed for both directions. To estimate the speed of the Y-stage, the average of the calculated speed values of all tested distances for the same direction has been calculated. The last row presents the estimated (mean) vertical speeds of the Y-stage (upward and downward).

Table 6: List of the time the Y-stage needed to move by several desired distances along the Y-axis in both directions, and the corresponding movement speed.

Desired distance (mm)	Upward direction				Downward direction			
	1.0	5.0	10.0	40.0	1.0	5.0	10.0	40.0
Measurement (n)	Time (s)							
1	0.81	2.65	4.82	17.99	0.86	2.49	4.91	18.66
2	0.80	2.58	4.68	17.92	0.82	2.60	5.01	19.10
3	0.84	2.63	4.58	19.23	0.81	2.64	4.82	19.23
4	0.86	2.56	4.73	17.98	0.85	2.43	4.85	19.74
5	0.82	2.58	4.79	19.17	0.84	2.67	4.91	20.38
Mean Time value (s)	0.83	2.60	4.72	18.46	0.84	2.57	4.90	19.42
Speed (mm/s)	1.21	1.92	2.12	2.17	1.19	1.95	2.04	2.06
Estimated Speed (mm/s)	**1.85**				**1.81**			

Figure 23 shows the graph that has been created to present the correlation of the desired distance and the time that the Y-stage needs to complete the desired movement.

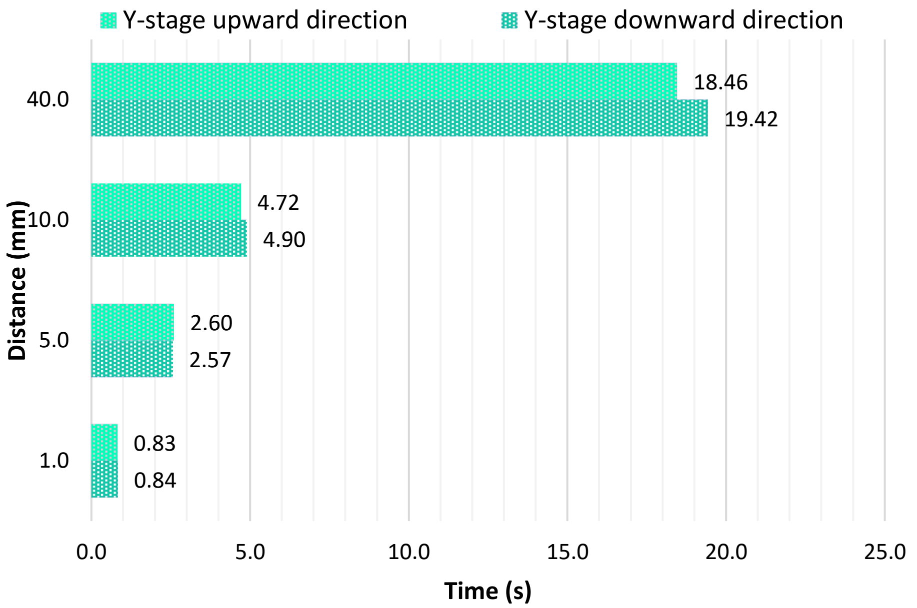

Figure 23: Graph of the time the Y-stage needed to move by the desired distances in both directions.

Estimation of X-stage motion speed

A similar estimation process as before was followed to estimate the movement speeds of motion that the X-stage produces. Figure 24 shows the developed set up that has been used to examine the X-stage motion.

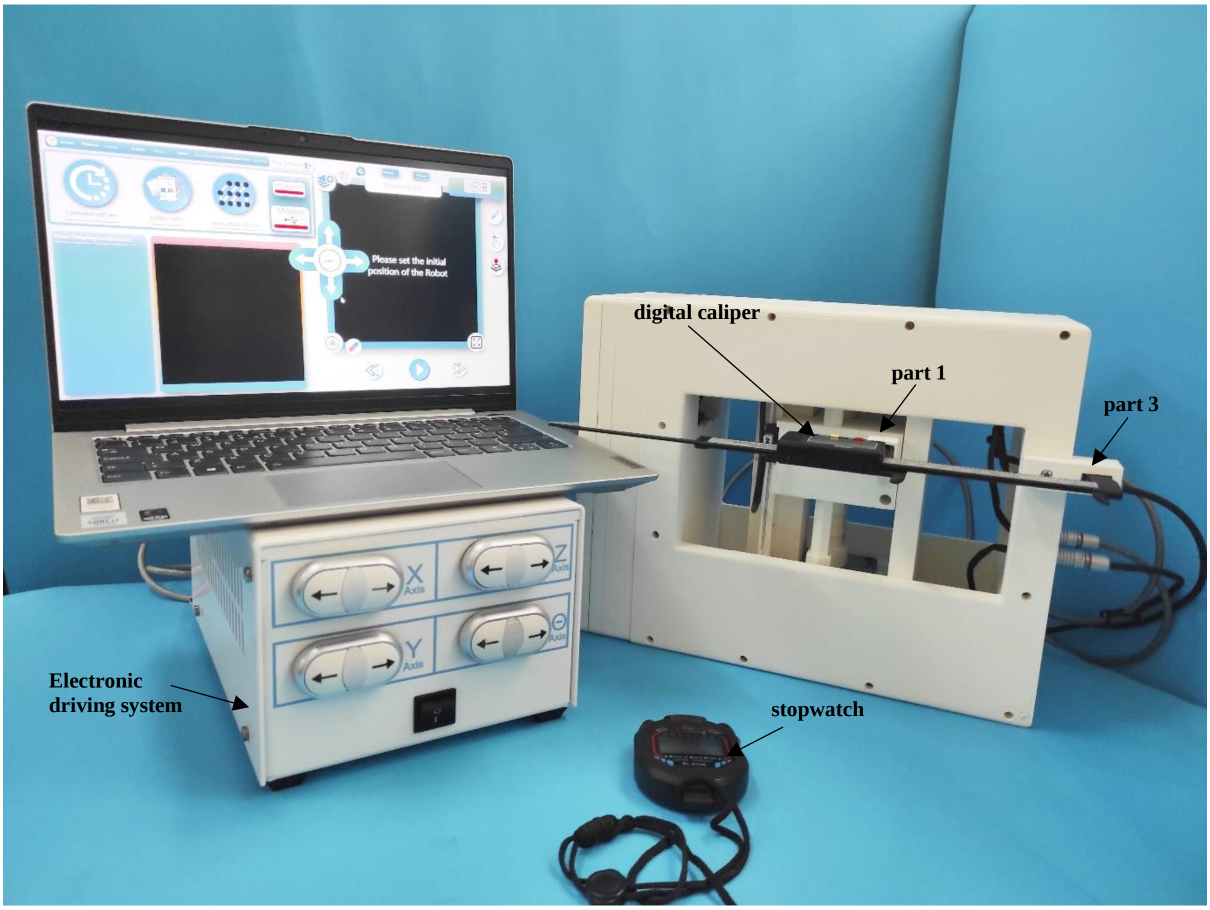

Figure 24: Experimental set up used to estimate the speeds with which the robotic system moves bidirectionally along the X-axis.

A stopwatch was used to count the time that the X-stage needed to cover the desired distances. Also, the two 3D printed parts 1 and 3 were used as the digital caliper's supporters. The digital caliper was used to ensure that the actual horizontal distance covered by the robotic system was equal to the desired one.

The desired motion was provided to the X-stage through the electronic driving system, which was connected to the special software. The user used the software to insert the respective input data for each desired motion. Due to the time delay between the beginning of the X-stage movement and the time the user sends the data, a time period called as response time of the X-stage was estimated. This time period is equal to the time delay occurred. Table 7 includes the measurements of the response time for several motion cases. The mean value of the measured response time has been estimated as the Table 7 shows.

Table 7: Response time of several measurements to estimate the mean response time of the X-stage motion.

Measurement (n)	Response time (s)
1	1.02
2	1.09
3	0.94
4	1.09
5	0.97
Mean Response time value (s)	1.02

The estimation process of the horizontal speed of the X-stage includes several time measurements. Specifically, for each direction, the robotic system was forced to move horizontally to cover 4 different desired distances. These desired distances are; 1.0 mm, 5.0 mm, 10.0 mm and 40.0 mm. The desired motions performed in the right direction have been separately examined from those executed in the left direction. As the Table 8 shows, the time period taken to complete each desired motion was counted. It is important to note that the presented values do not include the calculated response time. The left part of the Table 8 lists the respective measurements and calculations of the desired motions in the right horizontal direction. The right side presents the measurements and calculations performed when the system was forced to move along the X-axis in the left direction.

The last rows of the Table 8 list the results of the calculations that led to the estimation of the mean horizontal speed referred to as “estimated speed”. The mean value of the time that the robotic system needed to move by the desired distance was calculated for all the motion steps. Then, these values were used to estimate the X-stage’s speed at each case. Specifically, each desired distance was divided by the respective calculated mean value of time to estimate the horizontal speed. The average value of the calculated horizontal speeds was calculated for each direction separately. The (mean) estimated horizontal speeds in both directions are listed on the last row of the Table 8.

Table 8: List of the time the X-stage needs to move by several desired distances along the X-axis in both directions.

Desired distance (mm)	**Right direction**				**Left direction**			
	1.0	5.0	10.0	40.0	1.0	5.0	10.0	40.0
Measurement (n)	Time (s)							
1	0.71	1.78	3.13	11.08	0.68	1.77	3.27	11.18
2	0.58	1.74	3.05	11.16	0.72	1.83	3.32	11.21
3	0.72	1.73	3.06	11.11	0.69	1.79	3.23	11.18
4	0.68	1.76	3.11	11.15	0.68	1.81	3.20	11.20
5	0.70	1.78	3.18	11.14	0.68	1.76	3.27	11.18
Mean Time value (s)	0.68	1.76	3.10	11.13	0.69	1.79	3.26	11.19
Speed (mm/s)	1.48	2.85	3.22	3.60	1.45	2.79	3.07	3.58
Estimated Speed (mm/s)	**2.79**				**2.72**			

Figure 25 shows the graph to which the relation of the desired distance with the time that the X-stage needs to complete the desired movement is presented.

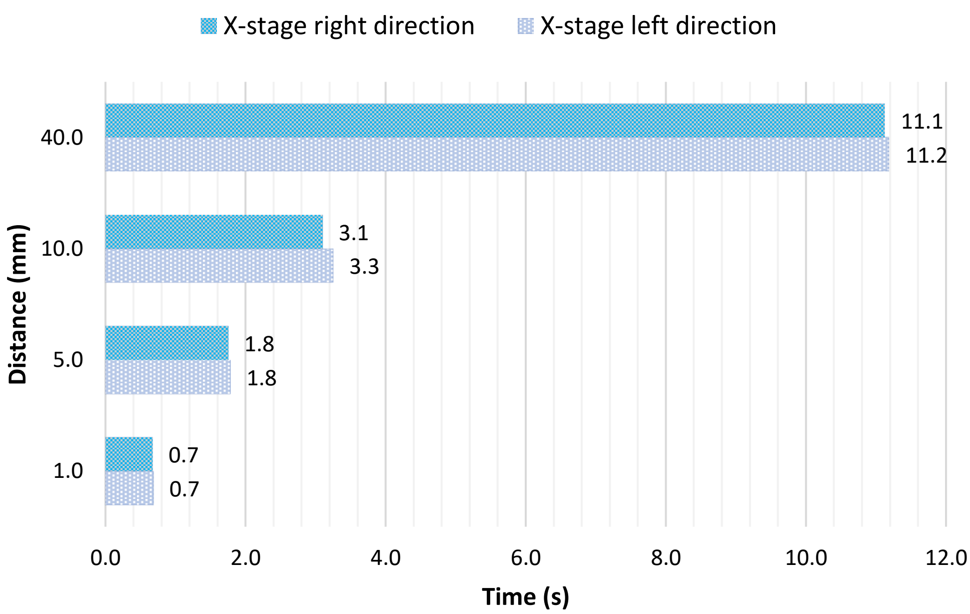

Figure 25: Graph of the time the X-stage needed to move by the desired distances in both directions.

Discussion

The current deliverable described the evaluation of the MRBREASTBIO system's motion accuracy and movement speed. Notably, the MRBREASTBIO robotic device is a two-DOF positioning device able to move along the Y-axis (vertical motion) and the X-axis (horizontal motion). These movements were performed individually to reach a desired position. The individual production of the motion stages led to the separated evaluation of their motion accuracy and the estimation of two speeds; the vertical speed and the horizontal speed.

Table 9: List of the estimated percentage error, the respective range of the measured distances and their mean value of each desired distance along both axes in all directions.

Desired distance (mm)	**1.0**		**5.0**		**10.0**		**40.0**	
Y-stage	Upward direction	Downward direction	Upward direction	Downward direction	Upward direction	Downward direction	Upward direction	Downward direction
	Range of measured distances (mm)							
	0.9-1.1	**0.8-1.1**	4.9-5.1	4.9-5.1	9.9-10.1	9.9-10.1	39.9-40.1	39.8-40.0
	Actual distance *(mean value)* (mm)							
	1.0	1.0	5.0	5.0	10.0	10.0	40.0	39.9
	Error (%)							
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**-0.30**
X-stage	Right direction	Left direction	Right direction	Left direction	Right direction	Left direction	Right direction	Left direction
	Range of measured distances (mm)							
	0.9-1.1	0.9-1.1	4.9-5.1	**5.0-5.1**	9.9-10.1	**10.0-10.1**	**39.8-40.1**	39.8-40.0
	Actual distance *(mean value)* (mm)							
	1.0	1.0	5.0	5.0	10.0	10.1	39.9	40.0
	Range of measured distances (mm)							
	0.00	0.00	0.00	0.00	0.00	**1.00**	**-0.30**	0.00

Table 9 lists the mean values of all the measured distances for all the desired distances that the robot undertaken throughout the entire evaluation process of accuracy. These desired distances were 1.0 mm, 5.0 mm 10.0 mm and 40.0 mm in both axes and directions. The mean values of the measured distances, defined as actual distances, and the respective desired distances have been considered to estimate the motion error. The motion error that is listed on Table 9 was calculated on a percentage scale to assess the robotic system's accuracy.

The range of measured distances for all the desired distances are listed in Table 9, as well. During the downward movement of 1.0 mm and the right movement of 40.0 mm, the maximum range of the measured distances has been observed. In contrast, the minimum range occurred when the robot has been assigned to move 5.0 mm and 10.0 mm along the X-axis in the left direction.

Figure 26 shows the graph that represents the desired distance related with the actual distance of each case. The error percentage is also presented as a function of the actual distance.

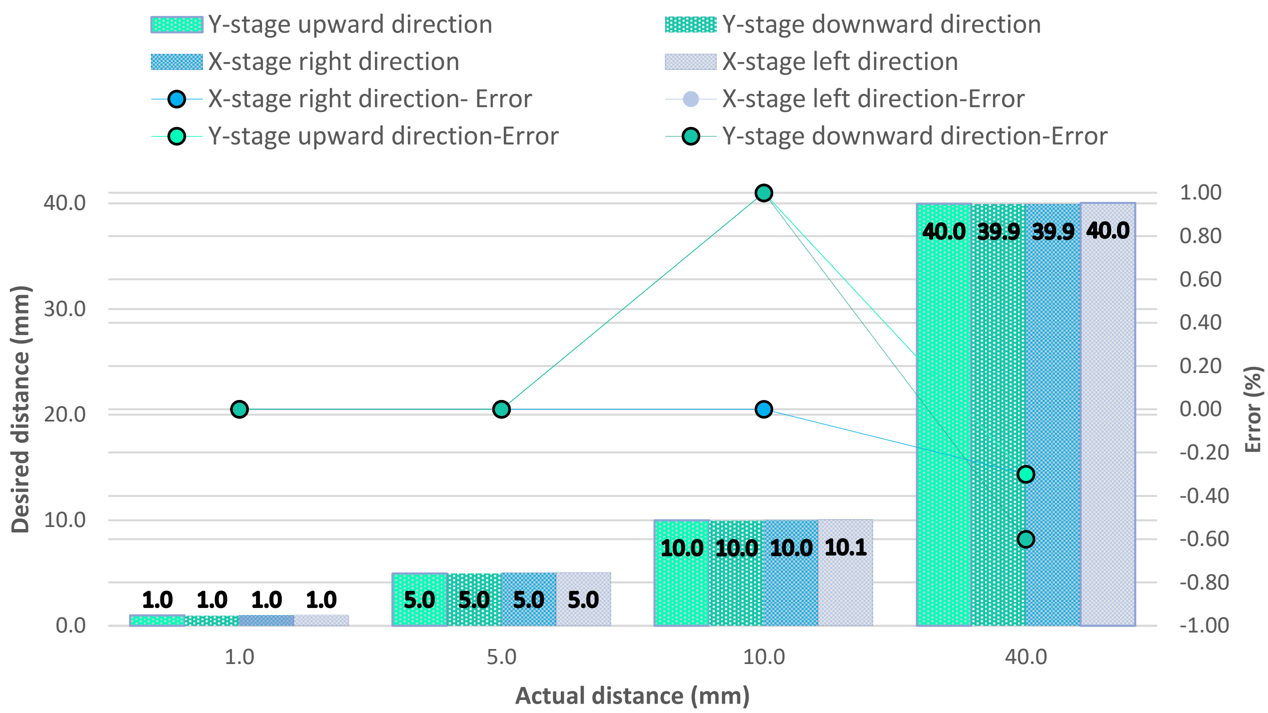

Figure 26: Desired distance versus Actual distance and the estimated error percentage of each desired motion in both axis in all directions.

The maximum error, which is equal to 1.00 %, occurred when the robot was forced to move along the X-axis left direction. The error of both right horizontal motion and downward vertical motion at 40.0 mm has been estimated as -0.30 %. The negative value shows that the evaluated actual distance was smaller than the desired one. The error value of the rest cases that have been examined to estimate the robotic system's accuracy was found to be 0.00 %.

Table 10 summarizes the calculations that have been done to estimate the movement speeds of the MRBREASBIO robotic device. The listed time values are those that have been estimated as the mean values of multiple measurements acquired in each axis and direction. The desired distances that the robot was assigned to cover along both motion axes and directions are; 1.0 mm, 5.0 mm, 10.0 mm and 40.0 mm.

Table 10: List of the mean value of the time the robotic system needed to execute each desired motion with the respective estimated (mean) speed values.

Desired distance (mm)		**1.0**	**5.0**	**10.0**	**40.0**	**1.0**	**5.0**	**10.0**	**40.0**
Y-stage		**Upward direction**				**Downward direction**			
	Time (s) *(mean value)*	0.83	2.60	4.72	18.46	0.84	2.57	4.90	**19.42**
	Speed (mm/s)	1.21	1.92	2.12	2.17	1.19	1.95	2.04	2.06
	Estimated speed (mm/s)	**1.85**				**1.81**			
X-stage		**Right direction**				**Left direction**			
	Time (s) *(mean value)*	0.68	1.76	3.10	11.13	0.69	1.79	3.26	**11.19**
	Speed (mm/s)	1.48	2.85	3.22	3.60	1.45	2.79	3.07	3.58
	Estimated speed (mm/s)	**2.79**				**2.72**			

The longest and most time-consuming motion that the robot has been assigned was to cover a distance equal to 40.0 mm. Considering the previously presented time values of this case, the left horizonal movement was slower than the right one , whilst the downward vertical movement needed more time to be completed than the upward one.

Figure 27 presents the graph that has been created to visualize the correlation between the calculated speeds and the respective desired distances. This graph includes all four estimated speeds. The estimated vertical speed when the robot is moving upwards is equal to 1.85 mm/s and 1.81 mm/s when is moving downwards. The horizontal estimated speeds when the robot is moving in the right and left directions are 2.79 mm/s and 2.72 mm/s, respectively. The faster linear motion was found in the Y-axis, provided by the Y-stage of motion.

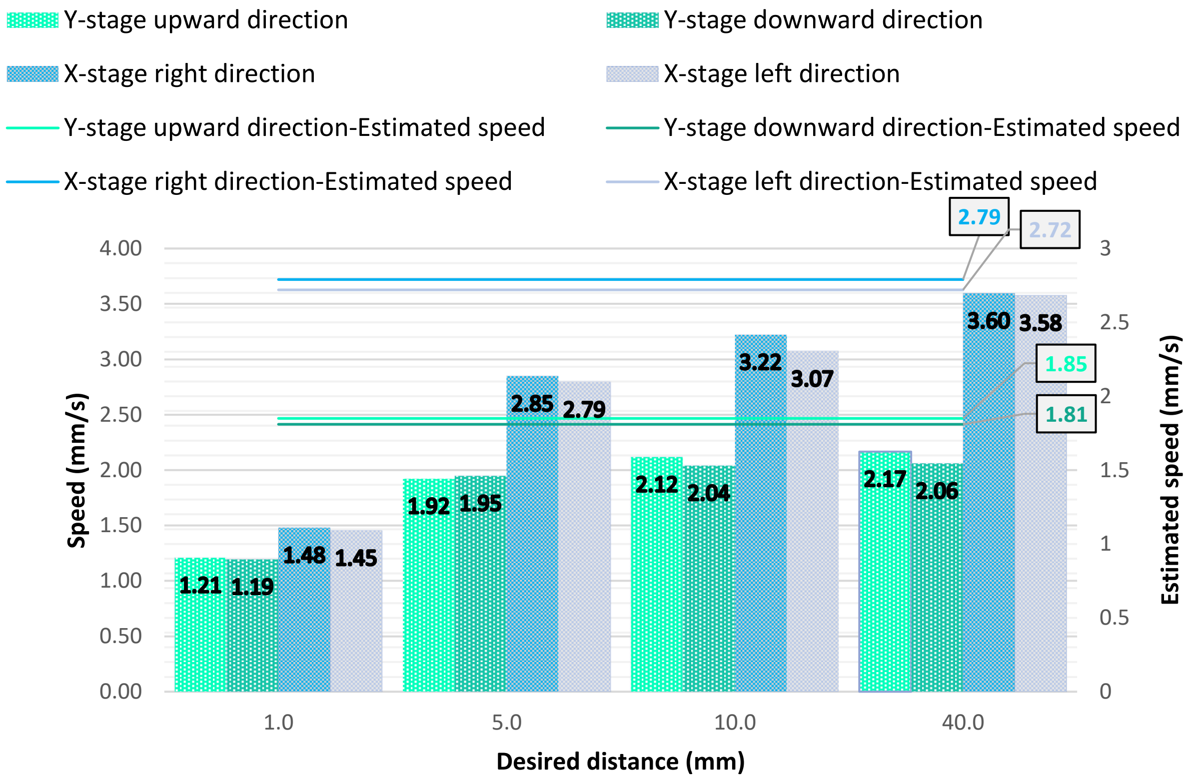

Figure 27: Movement speed calculated for each desired motion versus Desired distance and the estimated speed of both X and Y stages.