Workspace Analysis of a Collaborative Bi-manual Industrial Robotic System

Jovan Šumarac, Kosta Jovanović and Aleksandar Rodić

Abstract—**Bi-manual manipulation has been a focus of extensive academic research and has found its uses in industry as well. The workspace assessment of a robot is one of the key parameters in robot consideration for commercial purposes. As well, it is essential for the research of a bi-manual robotic system that often tends to replace humans in bi-manual tasks or directly share the workspace with humans. The goal of this paper is to present a detailed workspace analysis of a dual-arm collaborative robot. The dual-arm collaborative robot has been developed at the Robotics Laboratory at "Mihajlo Pupin" Institute and it is briefly presented in the paper. The workspaces of particular robot arms on the dual-arm system, a shared workspace for bimanual operation, and a manipulability analysis are presented. The simulations have been performed in Matlab, whereas CoppeliaSim robot simulator has been used for the visualization of the results. The presented results are an essential point in consideration of optimal trajectory planning and bi-manual collaborative robot control.**

***Index Terms*—Robot workspace; Bi-manual manipulation; Collaborative robots**

I. Introduction

Bi-manual or dual-arm manipulation is increasingly applied in modern robotics, and it is gaining further momentum with the advances in collaborative robotics. Bi-manual robots' similarity to human body form together with the need to replace human auxiliary work, as well as their increased workspace and task range are some of the main reasons. Similarity to human form also means easier integration of bi-manual robots in different environments originally intended for human workers, as well as for tasks which require human robot physical interaction. The analysis of the complete expanded workspace of such a robot, both in terms of reachability and manipulability, is very important for defining and coordinating its tasks.

Since its humble beginnings in 1940s and 50s mostly for tele-operation tasks, the development and research of bi-manual robots slowed down and gave way to single arm robots. However it again gained popularity and advanced significantly since the 1990s [1]. The focus was not only on scientific research, but also on producing commercial bi-manual robotic system.

Over the years many bi-manual robots were developed either for research or commercially. A detailed overview of the various scientific bi-manual platforms is given in [1]. Of those, the most interesting is Rollin' Justin [2]. It is a mobile robotic system and research platform that allows implementation of sophisticated control algorithms and dexterous manipulation. It is a powerful upper body humanoid robot with torso and two lightweight robot arms with four finger hands. Its workspace is quite large; its arm span is 3000 mm and the torso can move about 600 mm to the front and 300 mm to the back. However, a downside to this is that the robot is required to be mounted on a very stable base with a large footprint to prevent it from falling over.

In recent years, using collaborative bi-manual robots commercially has been a growing trend. In [3] a good overview of commercial bi-manual robots is given. The first such robot was called Baxter, presented in 2012 by Rethink Robotics. Its manipulator consists of a head, a torso and two arms with 7 degrees of freedom each. Its arm span is about 2600 mm and there is significant overlap between workspaces of both arms. Most of this common workspace is directly in front of the robot as it has a rotational limit at the shoulder [4]. ABB has also developed a commercial dual-arm collaborative robot called IRB 14000 Yumi. It can collaborate with a human and is intended for assembly of small parts. Its arms have relatively smaller ranges, about 560 mm each, resulting in a 1200 mm span and a smaller workspace[5]. Another smaller commercial bi-manual robot was also developed and presented by Epson in 2018, called the WorkSense W-01 with a similar arm range and workspace as Yumi [6].

The bi-manual robot analyzed in this paper was developed and made at the Robotics Laboratory at "Mihajlo Pupin" Institute. This paper presents the robot and an analysis of its workspace. The workspace is analyzed for each of the arms, and shared workspace is presented as well. Finally a manipulability analysis is performed. The simulation was done in Matlab and the results presented in CoppeliaSim robot simulator.

II. Workspace Analysis of a Bi-manual robot

The robot presented and analyzed in this paper was custom developed at the Robotics Laboratory [7]. The idea was to design and develop a cloud-enabled industrial human-size service robot. One of the main goals was to make it very

Jovan Šumarac is with the Robotics Laboratory,"Mihajlo Pupin" Institute, University of Belgrade, Volgina 15, 11060 Belgrade, Serbia (e- mail: jovan.sumarac@pupin.rs)

Kosta Jovanović is with the School of Electrical Engineering, University of Belgrade, 73 Bulevar kralja Aleksandra, 11020 Belgrade, Serbia (e-mail: kostaj@etf.bg.ac.rs)

Aleksandar Rodić is with the Robotics Laboratory, "Mihajlo Pupin" Institute, University of Belgrade, Volgina 15, 11060 Belgrade, Serbia (e-mail: aleksandar.rodic@pupin.rs)

versatile and applicable in different tasks. The goal was also to make it the first-generation intelligent industrial service robot, meaning it possesses a significant level of artificial intelligence (such as perception, task planning, decision making, etc.).

The robot consists of several functional modules. Its base is a motorized cart that serves as a mobile platform and allows the transportation of the bi-manual robotic system. The mechanical robot torso has 4 degrees of freedom and the robot arms are mounted on it. The arms are two UR5 lightweight industrial manipulators with 6 degrees of freedom by Universal Robots.

Each robot arm has several modules at its end effector including force/torque sensors, wrist cameras and industrial grippers. Each arm is mounted on the torso at an angle of about 15 degrees which results in a larger shared workspace. Fig. 1 shows the robot in virtual reality in CoppeliaSim robot manipulator.

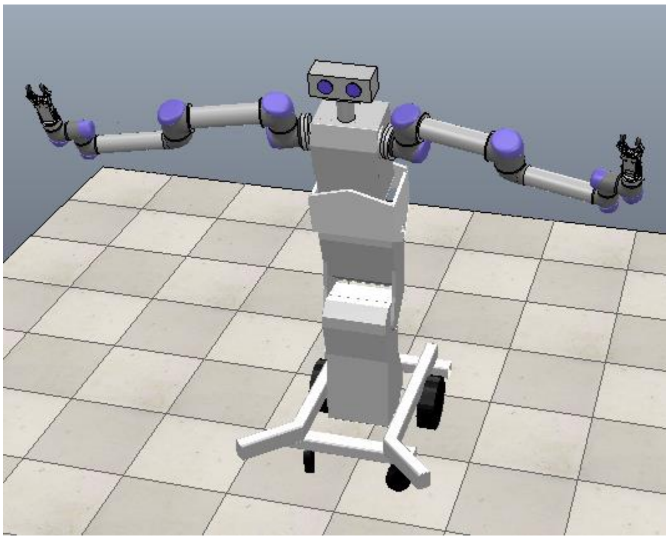

Fig. 1. The robotic system analyzed in this paper shown in a robot simulator

Fig. 1. shows the robot in a slightly bent forward torso configuration, which is common if the objects of interest are in front of the robot. It also shows the robot with a stylized head and eyes. This was done because the development of a vision and audio system is one of the goals for this robot as well.

The prototype of the mechanical torso currently developed at the Robotics Laboratory is shown in Fig. 2. The mechanical torso is of variable geometry. It can be in a standing position like in Fig. 2 which is its fully extended position. It can also be fully contracted e.g. in a bent position. In this paper the workspace analysis is performed for one, common configuration of the torso shown in Fig. 1. The results for the whole robot workspace for this torso configuration can easily be generalized for other torso positions.

A key issue in developing such a robotic system is defining and analyzing its workspace. Besides the obvious benefit of an increased workspace due to two robot arms, it is important to calculate the limits of the workspace in terms of reachability as well as identify problem areas within the workspace in terms of manipulability. This analysis is later used for designing the robots environment as well as the kind of tasks it will perform.

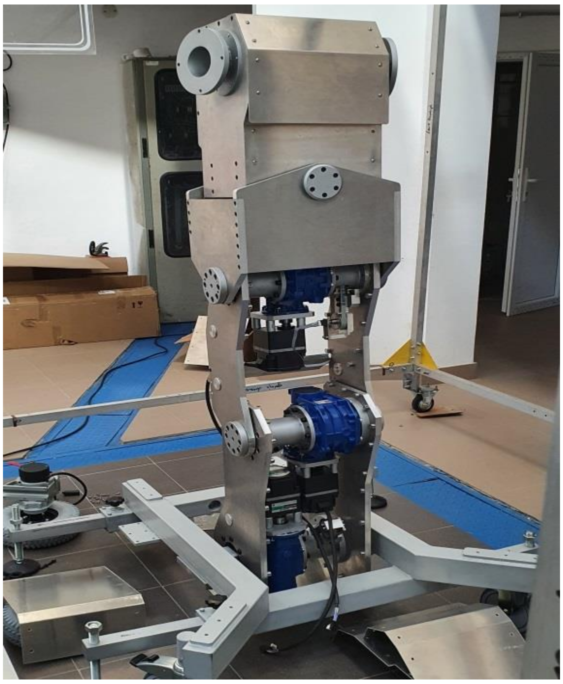

Fig. 2. The prototype of the mechanical torso of the analyzed robot.

Workspace analysis starts with the analysis of the individual workspaces of the robot arms. The arm ranges are provided by the manufacturer [8]. The idea behind the algorithm is to generate a relatively large number of random configurations within joint limits for both of the arms. Forward kinematics is then calculated to get the Cartesian coordinates of the end effector, and save its position for later drawing in the robot simulator. After visualizing the workspace in form of point clouds for each arm, the arm span and the volume of the shared workspace are calculated. This procedure is repeated for different numbers of random configurations. This is important for defining the reachability of the robotic system, e.g. the points in space it can reach.

Another important aspect of workspace analysis is finding the areas of reduced manipulability. The method for calculating manipulability in this paper was first described in [9]. The so-called Yoshikawa manipulability measure [10] describes how close the robot is to a singular configuration – e.g. how close it is to losing one of its degrees of freedom. The manipulability index is calculated as:

$$\boldsymbol{m} = \sqrt{\det(\boldsymbol{J}\boldsymbol{J}^{\boldsymbol{T}})} \tag{1}$$

where $\boldsymbol{J}$ is the Jacobian matrix of the robot arm at a certain configuration. This measure is proportional to the velocity ellipsoid at a given configuration. The velocity ellipsoid indicates the ability of the robot to move in each of the 3 translational and 3 rotational directions. If ***m*** equals zero it means that one degree of freedom is lost and that the robot is at a singular configuration. The bigger the index is, the more manipulability robot has in its current position. This measure is based only on the kinematics of the mechanism and does not take into account mass and inertia. Still, it's a good method for finding problem areas within the workspace that should be avoided in actual tasks.

The manipulability index is then calculated for all of the random configurations generated earlier. A cutoff index value is defined, below which a robot configuration is considered poorly manipulable. Percentages of such configurations for different number of random positions are calculated as well.

III. SIMULATION AND RESULTS

The system was modeled and the simulation was done in Matlab. Its' Robotics Toolbox package offers a number of ready-made functions, including the computing of forward, differential and inverse kinematics, trajectory planning, robot 3D animation, etc. After calculating the point cloud of reachable points, the workspace in body planes is shown in Matlab, while the visualization of the whole workspace and robot environment is done in CoppeliaSim robot simulator.

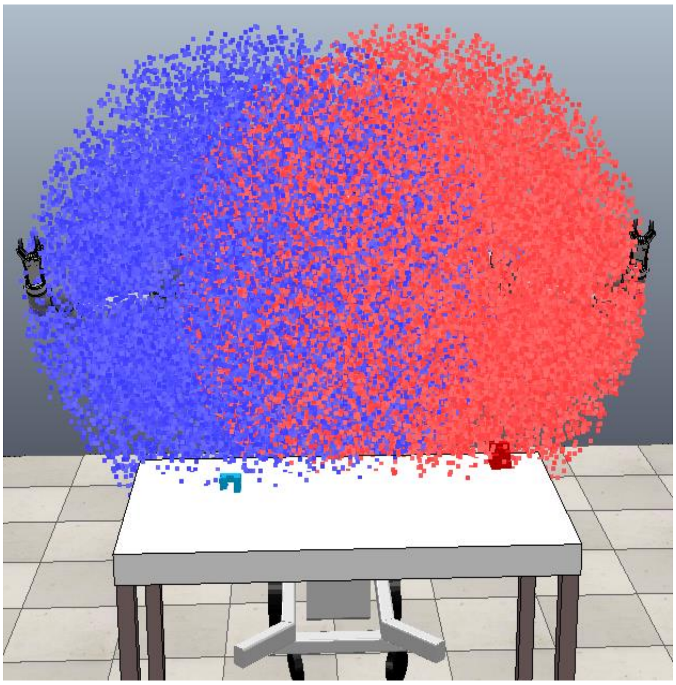

Fig. 4. Front view of the robot workspace in CoppeliaSim robot simulator.

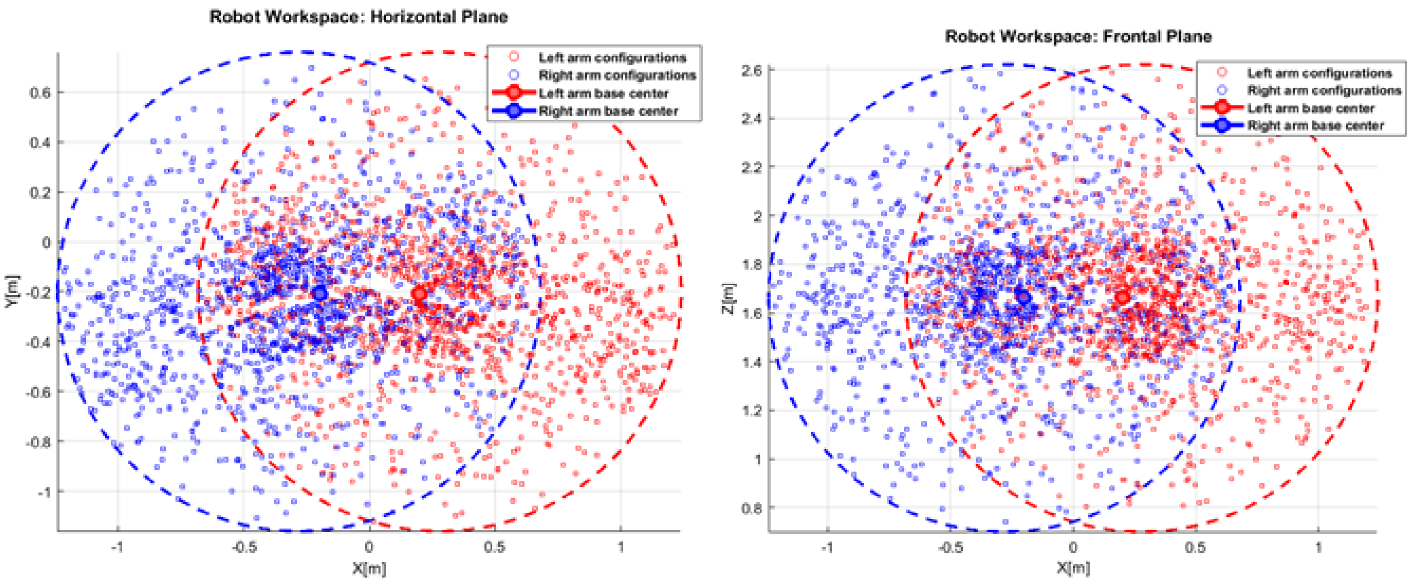

Fig. 3. Workspaces of the robot arms shown in horizontal (transverse) and frontal planes. The blue and red dashed lines mark the boundaries of the individual workspaces of the right and left robot arm workspaces, respectively.

Fig. 3 shows the robot workspace in horizontal and frontal body planes. The red points indicate the reachable points of the left arm while the blue ones are reachable for the right one. The individual arm workspaces are rounded with dashed lines so the shared workspace is easily identifiable.

Meanwhile, Fig. 4 shows the visualized workspace in robot simulator. The robot is in a slightly bent positon. A table with two objects (two parts) for an assemblage task is shown in front of it as an example of a typical task and typical robot environment. As in previous figure, the reachable points for the left and right arm are shown in red and blue, respectively.

So, the visualized workspaces show the reachable area for the robot arms and for the whole robotic system as well. Since each arm has a range of 950 mm the arm span of the whole robot structure is around 2300 mm. It has to be pointed out that UR5 arms themselves have a range of 850 mm. However, adding end effector equipment such as force sensors, wrist cameras and grippers extends that range. For this simulation only the grippers were added to the end effector resulting in a 100 mm larger range. The workspace volumes of the individual arms (the red and blue cloud points in Fig. 4) are around $3.6m^3$. The volume of the shared workspace, visible in

Fig. 4 as the area where blue and red points intersect is around 1.12 m^3. It is also clear from Fig. 4 that the objects on the table are clearly within the reachable area.

From Fig. 3 it is clear that the individual workspaces of the robot arms do not just intersect in the area in front of the robot, but also in the back, as well as above and below the top of the torso. This information can be useful for specific tasks.

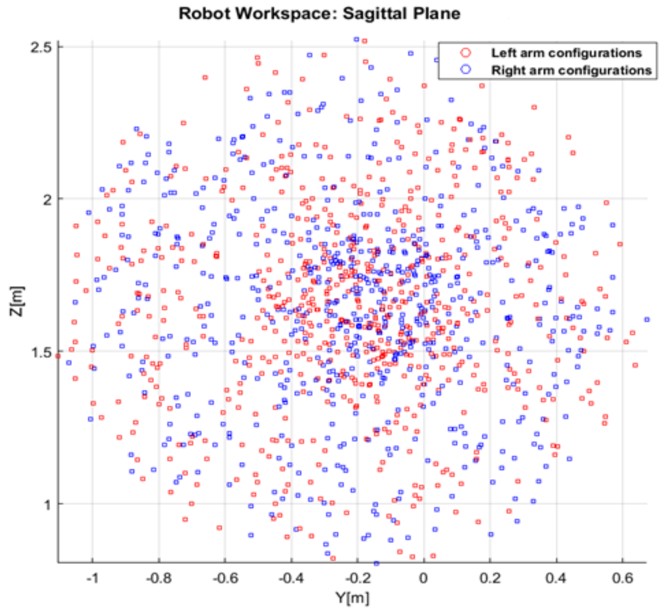

Fig. 5. Robot workspaces shown in sagittal plane.

Fig. 5 now shows the robot's sagittal plane. As its plane of symmetry, it contains similar number of configurations for both arms, equally and randomly distributed.

The robot structure itself is barely visible in Fig. 4. This is because of the relatively large number, 50000, of random configurations used for the simulation. Zooming into the point clouds in the robot simulator it can be seen that the points are equally distributed within the cloud (save for the areas in the torso which are not reachable). This is confirmed by Fig. 3 and Fig. 5 as well. These figures give the indication that all the areas within the workspace are equally reachable.

Manipulability analysis shows that that's not the case. Manipulability measure given with (1) is calculated for all the configurations used in mapping the workspaces. The key problem is identifying a key value of manipulability index, below which a configuration is considered poorly manipulable.

In [10] an index value of 10^{-5} is already considered quite poor, so a cutoff value of 10^{-4} is used to map problem areas within the workspace. Hence, the configurations with manipulability index of 10^{-4} or less are considered poorly manipulable (or "unmanipulable"). Configurations with the index between 10^{-4} and are 10^{-3} are relatively manipulable and those with the index bigger than 10^{-3} are not considered problematic.

Fig. 6. shows the robot system with the poorly manipulable points drawn. The points were calculated for each of the robot arms but were all drawn in the same color. The idea is to visualize them and identify problem areas to avoid for the whole robot in collaborative tasks.

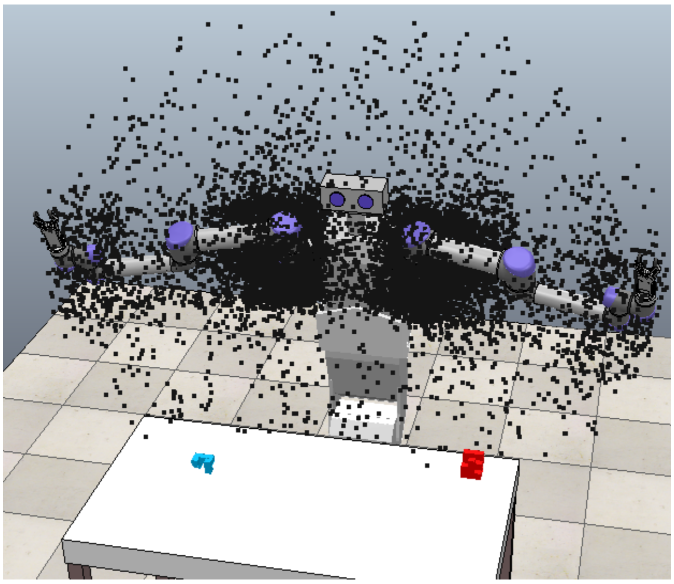

Fig. 6. Front view of the problem areas of the robot.

Clearly, there are clusters of problematic points around the bases of both arms and the first links as well as around the final links of the arms. On the other hand, there are no clusters in the area in front of the robot, closer to the table with the objects. Those are the least problematic areas which is important to know for practical tasks.

Fig. 6 shows only the points with the manipulability index equal to or less than 10^{-4}. If the relatively manipulable points were added too they would continue to cluster around the same locations. The areas which are in front of, behind, above and below the upper part of the torso, but which are a bit further from it, still remain the least affected by problematic points.

To corroborate this, and have a more detailed look into the structure of the problem areas it is good to again show the robot's body planes. This time they will be shown with unmanipulable configurations.

Fig. 7 shows the robots' horizontal and frontal planes. The problematic configurations are shown in the same color for both arms, to indicate problem areas for the whole robotic system, not just the individual arms. Again, it is evident that the least problematic areas are further away from the top of the torso in both directions.

These results again confirm the clustering of the problematic points around the top of the torso and to a lesser extent around the end effectors. The whole areas around the top part of the torso and the robot bases and first links form a clearly problematic region that should be avoided in tasks. However, this is not a practical problem for the robot. Since that region is very close to the location of the torso itself, many of those configurations are unreachable in any case, as the robot arms cannot be allowed to collide with the torso.

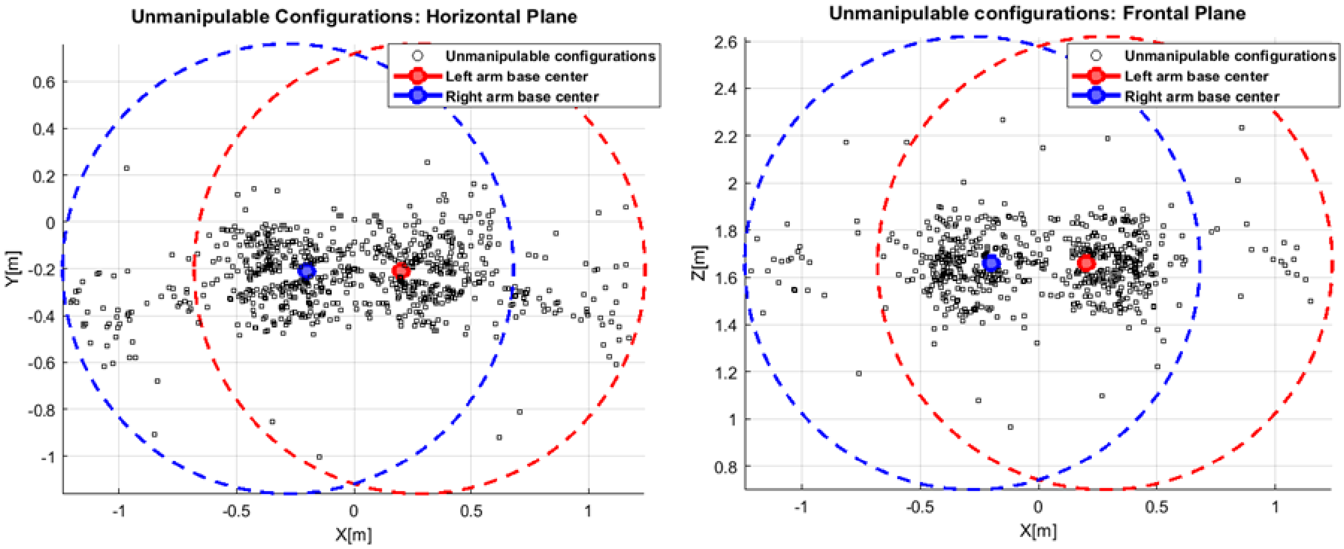

Fig. 7. Robot workspace with unmanipulable configurations shown in the horizontal and frontal plane of the robot's body.

It is interesting to analyze the number of poorly manipulable configurations, as well as the size of the manipulability index. The simulations were carried for a varying number of robot configurations, from 5000 to 50000 random positions.

The results are shown in Table I. They are shown for a single UR5 robot arm (the left one), since they are very similar to the other one.

TABLE I
MANIPULABILITY ANALYSIS

Number of configurations	Maximum manipulability index value	Minimum manipulability index value	Poorly manipulable configuration percentage
5000	0.1161	$8.472 \cdot 10^{-8}$	15.98
50000	0.1189	$1.124 \cdot 10^{-9}$	12.24
100000	0.1195	$5.710 \cdot 10^{-9}$	12.40
500000	0.1197	$1.338 \cdot 10^{-10}$	12.32

The final column shows the percentage of robot configurations with manipulability index less than 10^{-4}. It is the value below which a configuration is considered to have poor manipulability, as stated above. The percentage varies between approximately 16% for 5000 configurations to about 12.3% for a larger number of points.

The minimum value of the index is around 10^{-9}, which is pretty close to a singular configuration. The maximum value peaks at about 0.12, for the biggest number of robot configurations. While that indicates configurations with much more manipulability, the index is still not very high.

This shows that in practice, a seemingly large robot workspace can be significantly reduced by various limitations. Joint limits, self-collisions, singularities, and areas of reduced manipulability greatly impact its workspace and the way robot tasks can be defined and executed.

Another way of illustrating the manipulability in certain configurations is to show the robot with its velocity ellipsoids drawn. They are usually shown for the three translational components of the velocity. The volume of the ellipsoid is proportional to the manipulability at a given configuration. The longer the ellipsoid is along one of its axes, the more the robot can move in that direction and vice versa. If the configuration is singular the ellipsoid collapses into a planar ellipse as it loses one degree of freedom. If it loses another degree of freedom it can further collapse into a line.

The ellipsoids are shown here for three characteristic robot configurations. For the first one the robot arms are assembling an object directly in front of it, equally distanced from both arms. The second configuration is quite similar but the object is in front of the left arm base. The third is the initial configuration of the robot with its arms completely spread.

The results are shown in Fig. 8, 9 and 10. They are plotted in Matlab. The torso and the arms are shown as a kinematic chain and the ellipsoids are plotted at the arms' end effectors. The colors are again red for the left arm and blue for the right one.

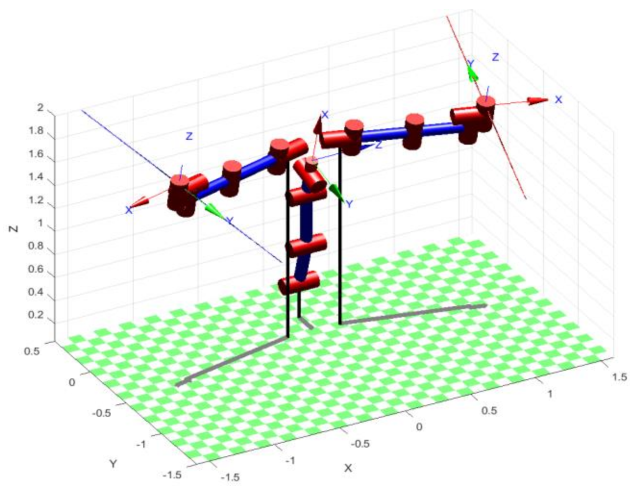

Fig. 8. Velocity ellipsoids in initial position.

The initial position is shown first and it is immediately clear that it is a singular configuration for the arms. Only lines are plotted meaning the robot loses two degrees of freedom and can only move in one translational direction.

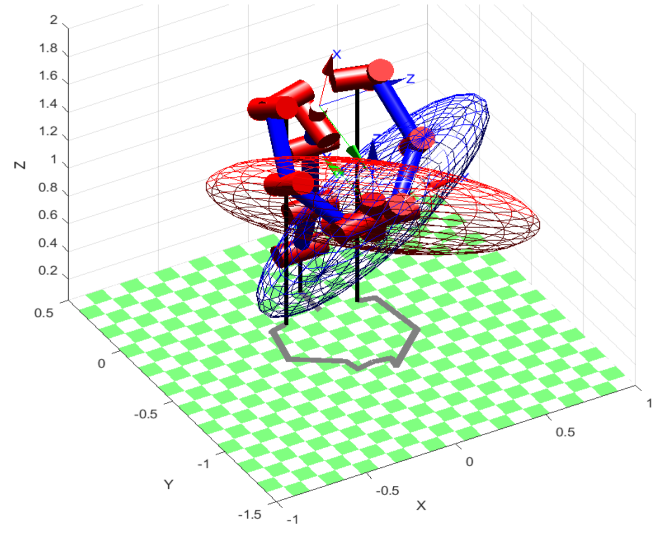

Fig. 9. Velocity ellipsoids in an assembly task in front of the torso

Fig. 9 shows the assembly position in front of the torso. The object is at an equal distance from both arms, and the ellipsoids are clearly much bigger, and equal to each other, indicating good manipulability.

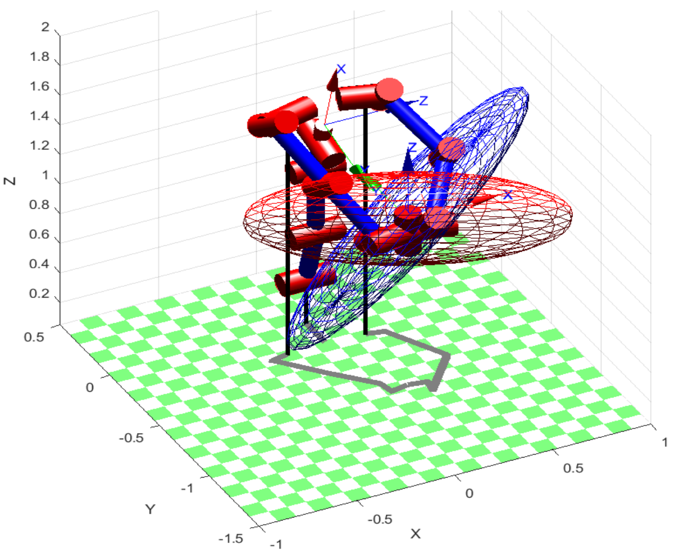

Fig. 10. Velocity ellipsoids in an assembly task in front of left arm base

Fig. 10 shows a similar task, this time in front of left arm basis. The shape of the left arm ellipsoid (red) remains similar while the right one is longer in one direction but quite shorter in another, which indicates a decreased manipulability for the right arm, which is expected.

IV. Conclusion

Simulation results have given a good overview of the workspace of a bi-manual robotic system. They have shown a large reachable area of the whole robot as well as a considerable shared workspace. Defining this workspace is very important as one of the early steps in developing a custom bi-manual robotic system. This information is essential for configuring the robot's environments and for defining its various future tasks.

Manipulability analysis has identified problem areas within the reachable workspace as well as areas of good manipulability. This is important for defining the way the robot will perform its tasks and its optimal trajectories.

While a good indicator of the robot's manipulability, this analysis is not perfect. It only takes into account the kinematic properties of the robot, and it does not mean that all of the unmanipulable or relatively manipulable configurations will present a problem for the physical robot. Still, it does give a good overview of the areas that should be avoided.

This paper presented a starting work in the analysis of a custom bi-manual robotic system. A more detailed manipulability analysis, that takes into account the masses and inertias of the mechanism could be performed, and compared with previous results. The authors' future work will also consider various other aspects of bi-manual robotic systems such as different control strategies, trajectory planning, etc.

V. Acknowledgements

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