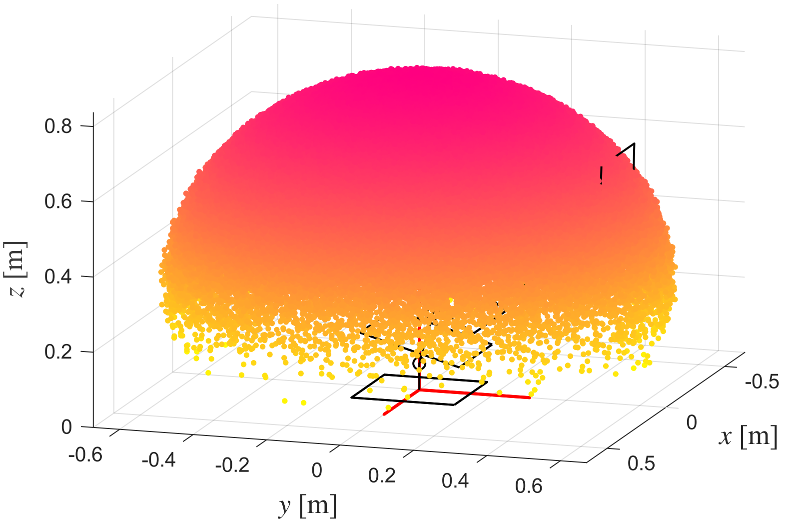
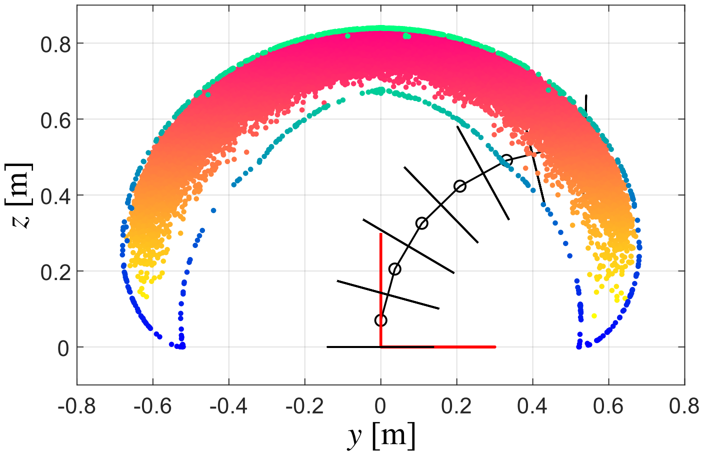
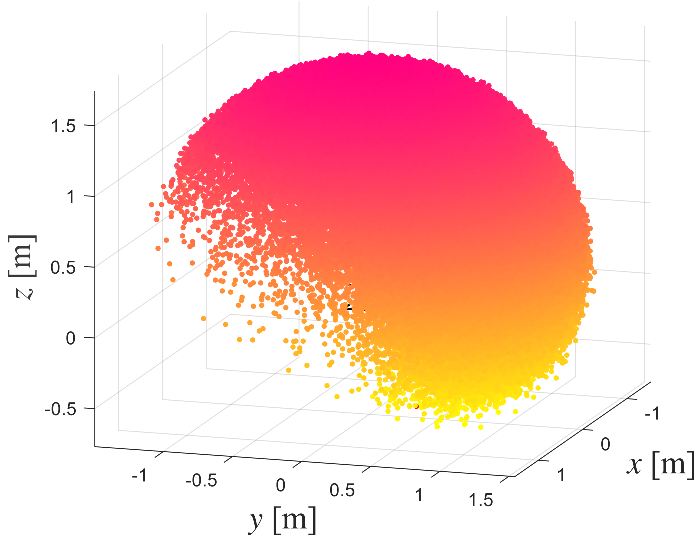


(a) Complete workspace view generated with Monte Carlo method

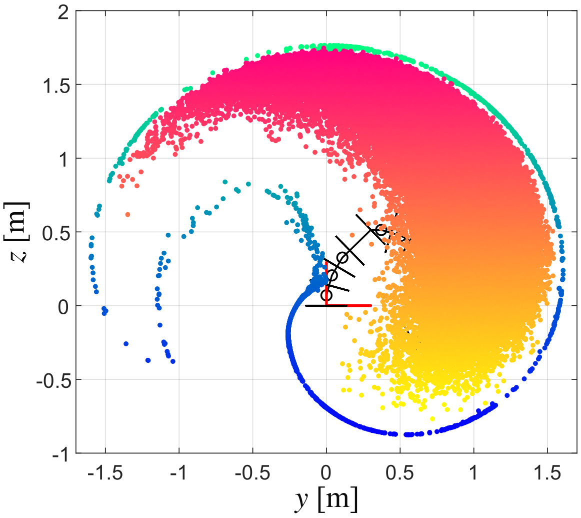


(b) Vertical section in $yz$-plane with comparison between optimized ray-based and Monte Carlo workspaces

Figure 5.16: Workspace points generated with Monte Carlo method describing NB-R2 workspace and comparison with optimized ray-based process results. Red-yellow points are generated with the Monte Carlo method. Blue-green points are generated with the optimized ray-based method.



(a) Complete workspace view generated with Monte Carlo method



(b) Vertical section in $yz$-plane with comparison between optimized ray-based and Monte Carlo workspaces

Figure 5.17: Workspace points generated with Monte Carlo method describing NB-R3 workspace and comparison with optimized ray-based process results. Red-yellow points are generated with the Monte Carlo method. Blue-green points are generated with the optimized ray-based method.

## 5.5 Proposed workspace surface plot

After computing the points on the workspace boundaries, it is necessary to interpolate them to generate the workspace surface. This section describes the algorithm to interpolate all the points and plot the workspace surface. This procedure makes it possible later to compute other workspace features like its surface area or volume. Moreover, an automatic process to determine the reachability of a 3D point could be implemented. However, the interpolation process presented here applies only to symmetrical workspaces. This means that only the workspace surfaces of the NB-R1 and NB-R2 can be computed. The NB-R3 workspace has a too complex non-symmetrical shape and can not be interpolated in a surface at the moment. Firstly, the point interpolation and surface generation method is explained. Then, the NB-R1 and NB-R2 workspace surfaces are shown.

This surface plot process is developed using the program MATLAB. Starting from the workspace point cloud, a cubic grid that contains all the points is created in the 3D space using the function `meshgrid`. This grid comprises several equidistant nodes spread along all the axes $x$, $y$ and $z$ that will be used for the first part of the process. A smaller step between each node leads to more nodes and a denser grid. Then, the generated points are substituted with the closest node on the previously defined 3D grid. More than one point can be substituted with the same node on the grid. This means there will be at most as many nodes on the workspace boundary as the generated points. So, a denser grid will lead to a more accurate surface plot. Figure 5.18 shows the selected nodes closer to the determined workspace boundary points. The set of these nodes is called $A$ and the coordinates are named $(x_A, y_A, z_A)$.

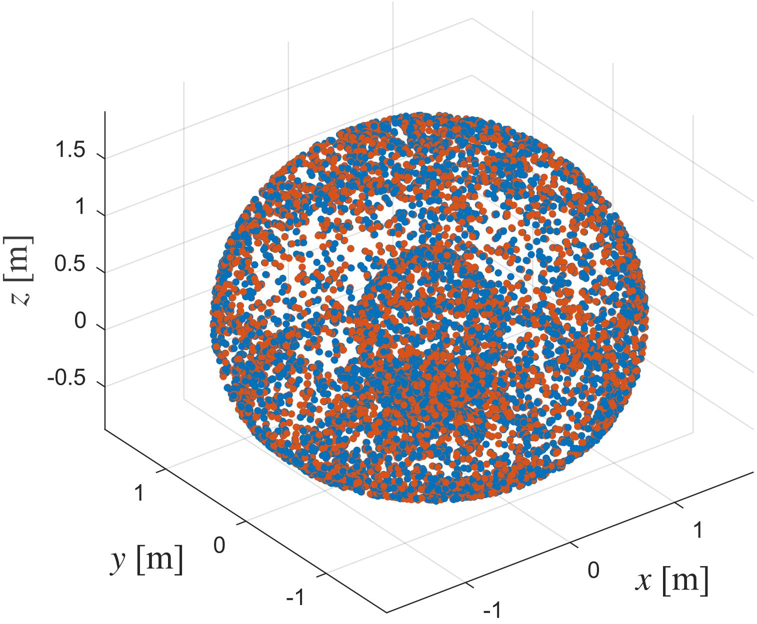
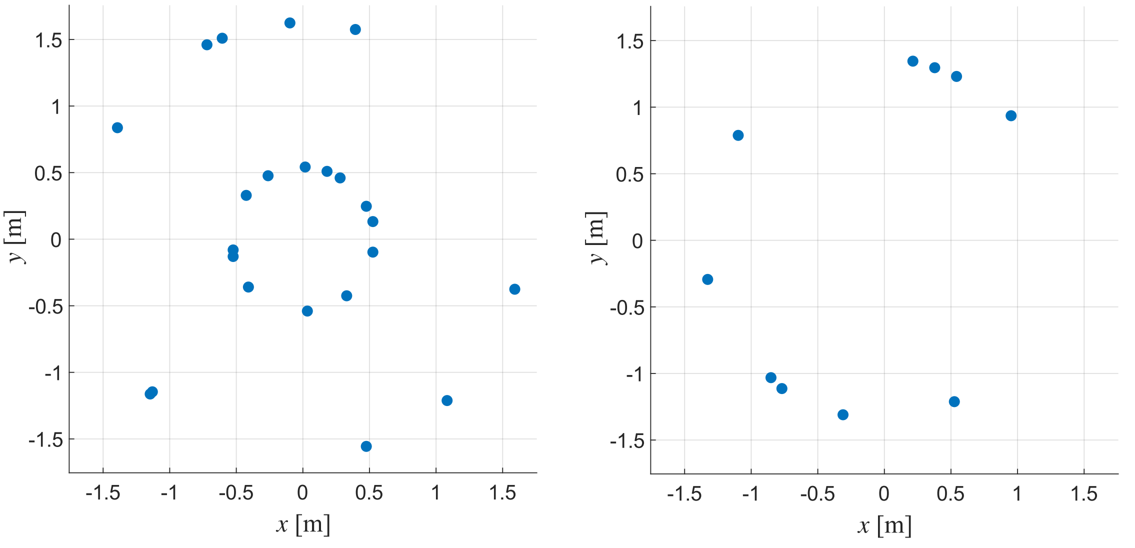


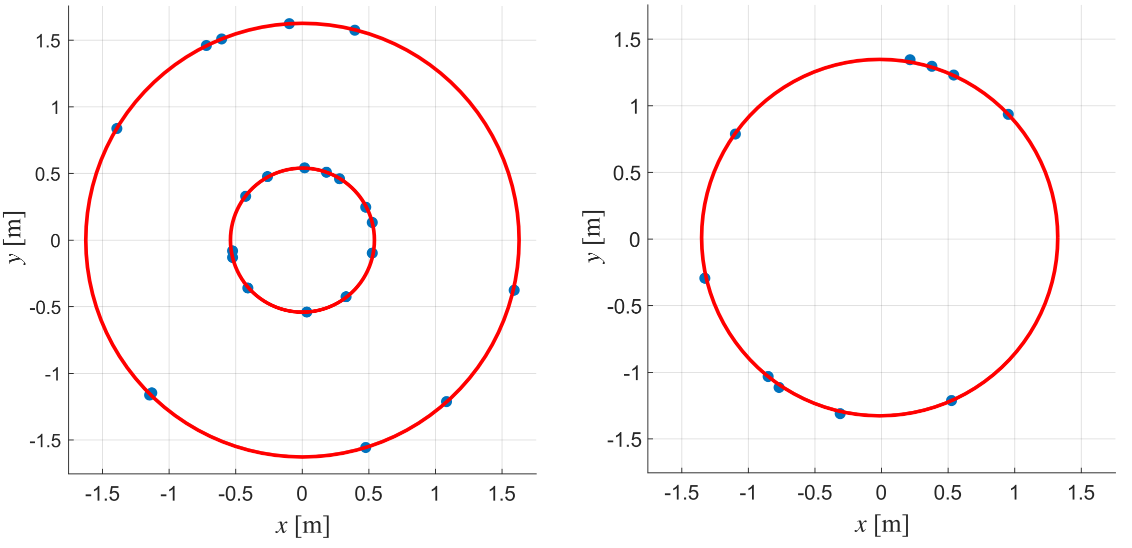
Figure 5.18: NB-R1 workspace boundary points in red and selected nodes on grid in blue

The interpolation process starts sectioning the grid along axis $z$. As shown in Fig. 5.19, a $xy$ section of Fig. 5.18 shows one or two circumferences for the symmet-



(a) Selected grid nodes at height $z_A = 0.11$ m (b) Selected grid nodes at height $z_A = 1.13$ m

Figure 5.19: NB-R1 selected nodes on grid for some horizontal sections in $xy$-plane for grid value $z_A$ along $z$



(a) Selected grid nodes at height $z_A = 0.11$ m (b) Selected grid nodes at height $z_A = 1.13$ m

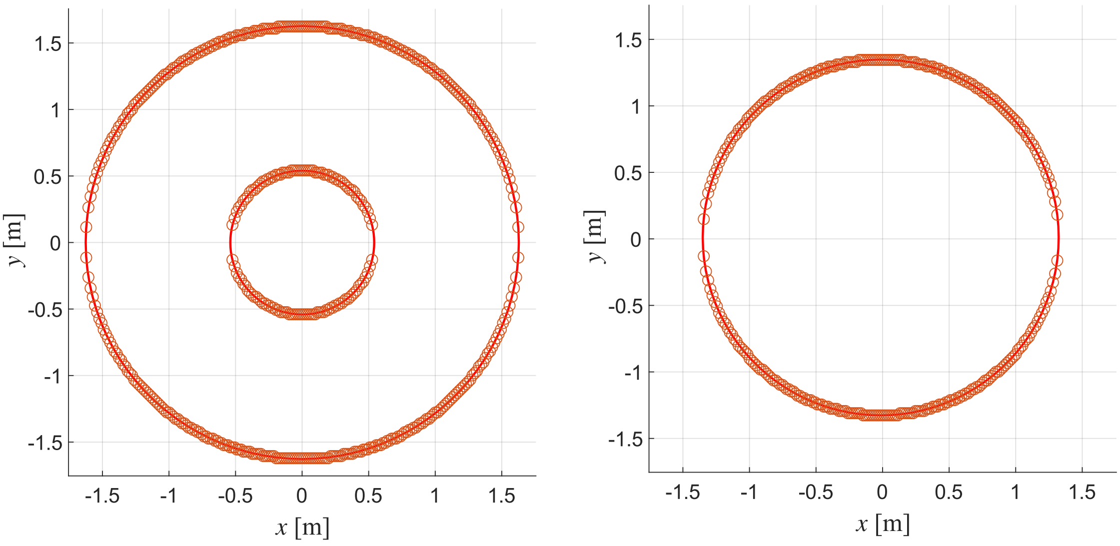
Figure 5.20: Reconstructed circumferences with center $(x_c, y_c)$ and radius $R_1$ and $R_2$ starting from the NB-R1 selected nodes on grid for some horizontal sections in $xy$-plane for grid value $z_A$ along $z$

rical workspaces based on the height along $z$. These nodes are identified by $A(z_A)$ where $z_A$ is a grid value along $z$. They are interpolated to identify the coefficients of two circumferences that pass through the nodes. Only one circumference is considered when the identified circumferences are too close because the nodes form just one circle, as shown in Fig. 5.19b. A minimization problem is solved to obtain the coefficients of the circumferences.

$$\begin{aligned} \min_{\substack{x_c,y_c,\\ R_1,R_2}} \quad & \operatorname{avg}\{((x_A - x_c)^2 + (y_A - y_c)^2 - R_1)((x_A - x_c)^2 + (y_A - y_c)^2 - R_2)\} \\ & \forall (x_A, y_A) \in A(z_A) \end{aligned} \tag{5.3}$$

The Eq. 5.3 minimize the average distance of each point from the two circumferences identified by the same center $(x_c, y_c)$ and radius $R_1$ and $R_2$. If the difference between $R_1$ and $R_2$ is under a certain threshold, only one circumference is considered. This process is repeated $\forall z_A \in A$. The reconstructed circumferences starting from the selected nodes are plotted in Fig. 5.20.

At this point, one or two circumferences have been identified on each grid height. The second part of the interpolation process starts and the previous 3D grid is deleted. A new grid is initialized equal to the previous one. All the nodes that compose this new grid are collected in a set called $B$ with coordinates named $(x_B, y_B, z_B)$.



(a) Selected grid nodes at height $z_C = 0.11$ m (b) Selected grid nodes at height $z_C = 1.13$ m

Figure 5.21: New selected nodes on grid in coincidence with the obtained circumferences for the NB-R1 workspace for some horizontal sections in $xy$-plane for grid value $z_C$ along $z$

**Algorithm 5.2** Grid node coefficient assignment

```
Require: Grid around the desired generated workspace, called $B$, and nodes on grid
    with coordinates named $(x_B, y_B, z_B)$. Selected nodes on the workspace boundary
    $C$ with coordinates named $(x_C, y_C, z_C)$.
Initialize variable sign $s = -1$.
for $\forall z_B \in B$ do
    for $\forall x_B \in B$ do
        for $\forall y_B \in B$ do
            Compute minimum distance $d$ between $y_B$ and closest $y_C$.
            Assign value $s \doteq d$ to node $(x_B, y_B, z_B)$.
            if $d = 0$ then
                Switch sign $s = -s$ because passed node $(x_C, y_C, z_C)$ on boundary.
            end if
        end for
    end for
end for
```

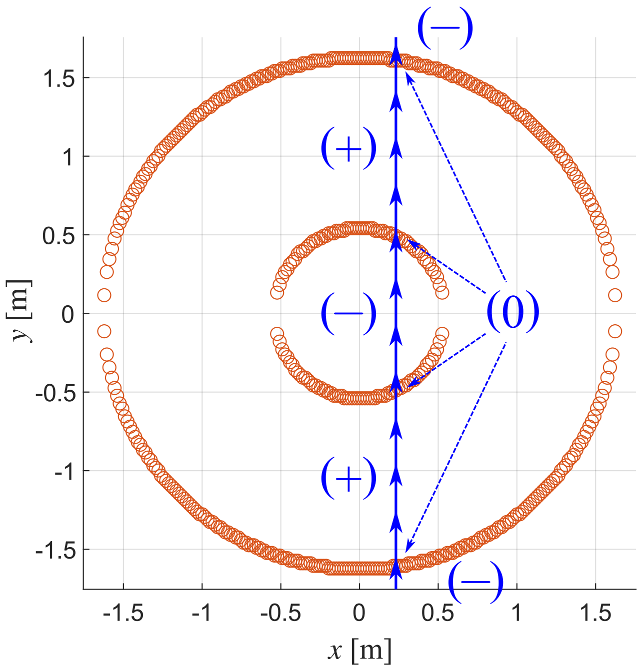
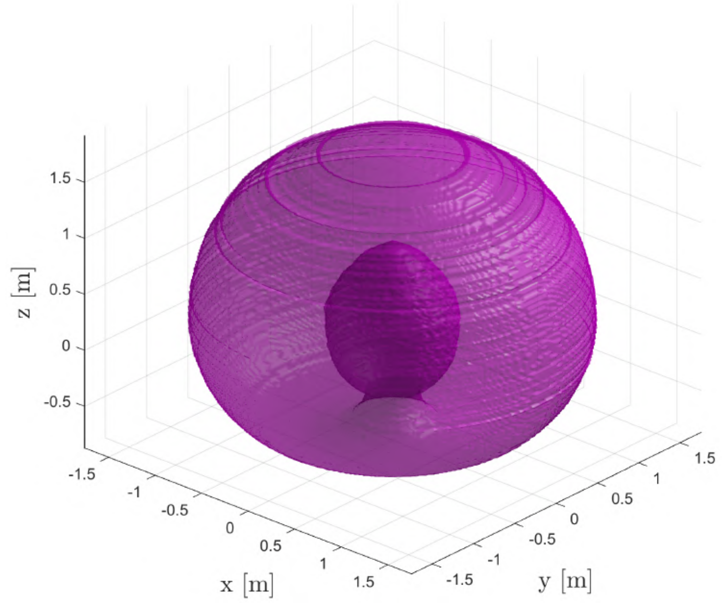
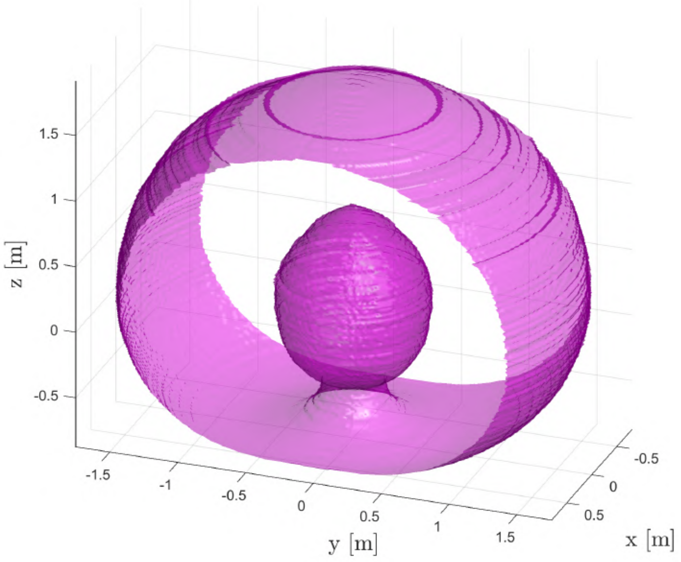


Figure 5.22: Processes of coefficient value assignment to each node in the grid built on the NB-R1 workspace for some horizontal sections in $xy$-plane for grid value $z_B$ along $z$. Full procedure explained in Algorithm 5.2.

The nodes that coincide with the computed circumferences are also collected in another set called $C$ with coordinates $(x_C, y_C, z_C)$. So, the set $C$ is composed of the nodes on the workspace boundaries. Figure. 5.21 shows the selected nodes that coincide with the circumferences. After this step, a positive or negative coefficient is assigned to each node of the set $B$. This coefficient is equal to the minimum distance $d$ between $y_B$ and closest $y_C$ for each couple $(x_B, z_B)$. A positive coefficient is assigned when the node is inside the workspace and becomes negative for the nodes outside. When $y_B$ and $y_C$ are equal, a 0 value is assigned since that node is on the workspace boundary. Algorithm 5.2 and Fig. 5.22 summarizes this procedure.

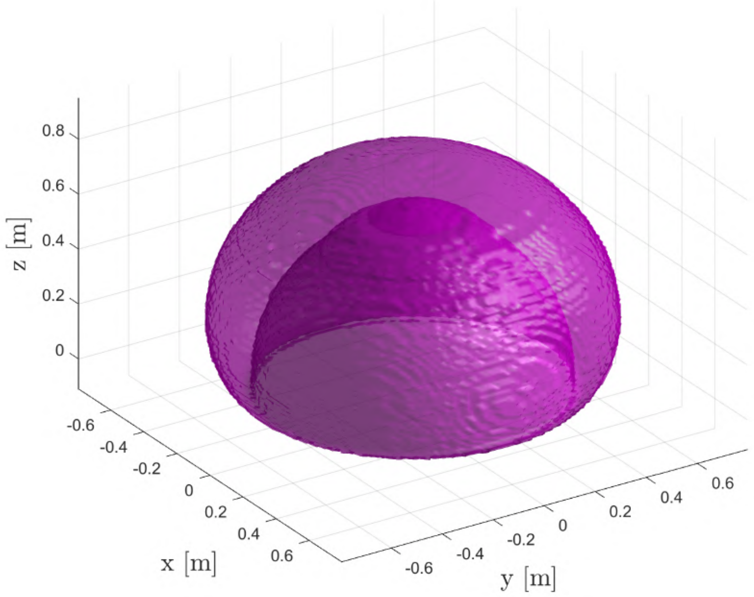


(a) Complete workspace view

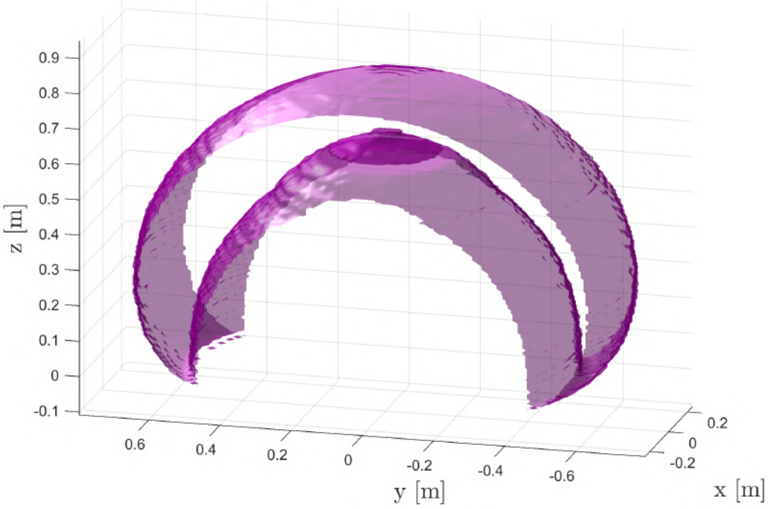


(b) Internal workspace view

Figure 5.23: Surface of the NB-R1 workspace generated interpolating the points obtained with the workspace determination algorithm



(a) Complete workspace view



(b) Internal workspace view

Figure 5.24: Surface of the NB-R2 workspace generated interpolating the points obtained with the workspace determination algorithm

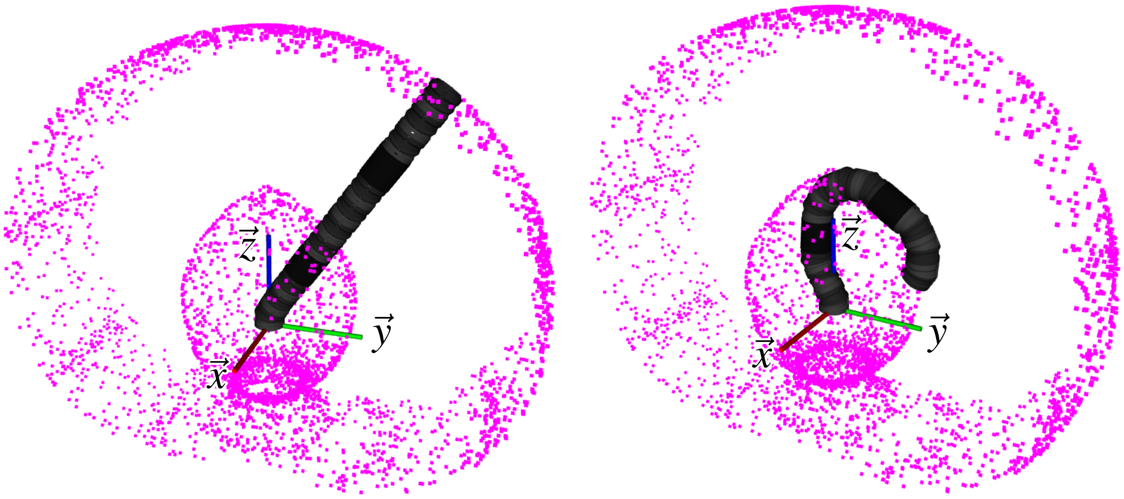
Once, a coefficient is assigned to each node, it is possible to use the `isosurface` function for generating and plotting the workspace boundary surface. Figure 5.23 shows the surface of the NB-R1 workspace, both 3D and inner views. In the NB-R1 case, the grid had a step of 0.03 m. Figure 5.24 shows the surface of the NB-R2 workspace, both 3D and inner views. In the NB-R2 case, the grid had a step of 0.01 m. The surface has been fully reconstructed and is easy understandable. This method can be applied only to the NB-R1 and NB-R2 robots because they are symmetrical and the circumferences can be used to interpolate the point. The

NB-R3 workspace boundaries have too complex shapes for this interpolation process.

## 5.6 Discussion about the proposed workspace determination algorithm

This section highlights some limitations of the proposed workspace determination algorithm. The first major limitation is the missing prior knowledge about the analyzed manipulator workspaces. So, there is no way to ensure the correctness of the result obtained by this algorithm. However, one way to check the result correctness is by plotting some robot configuration for each workspace. Figure 5.25 shows the NB-R1 robot CAD model plotted using ROS RViz tool in two different configurations with the end-effector on the detected boundaries. The obtained workspace points are shown in magenta. Trying to move the robot further, reaching a position outside this workspace is impossible. So, the correctness of the workspace detection is demonstrated by testing. Figures 5.26 and 5.27 show the NB-R2 and NB-R3 robot CAD models, respectively, in two different configurations with the end-effector on the detected boundaries. The obtained workspace points are shown in magenta. ROS RViz tool is again employed to plot the robots and their workspaces. The same test can be performed to prove the result fidelity.

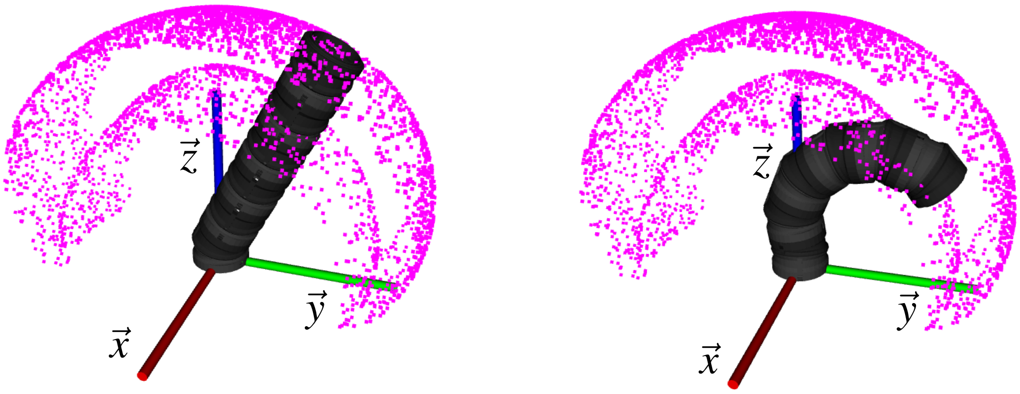
The proposed algorithm correctly identified the inner boundaries of the previous



(a) Robot on external boundaries

(b) Robot on internal boundaries

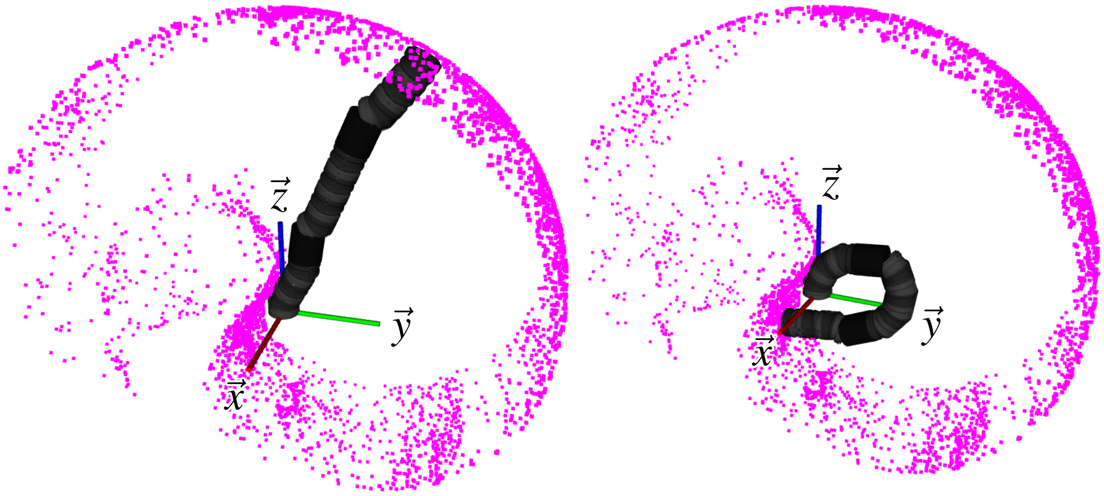
Figure 5.25: NB-R1 robot configuration on two collected points by the workspace determination algorithm. Obtained workspace points highlighted in magenta.



(a) Robot on external boundaries

(b) Robot on internal boundaries

Figure 5.26: NB-R2 robot configuration on two collected points by the workspace determination algorithm. Obtained workspace points highlighted in magenta.



(a) Robot on external boundaries

(b) Robot on internal boundaries

Figure 5.27: NB-R3 robot configuration on two collected points by the workspace determination algorithm. Obtained workspace points highlighted in magenta.

robot workspaces. However, the inner boundary detection can lead to errors when the number of NB-modules increases. Figures 5.28 and 5.29 show two Nimbl'Bot robot composed of 12 and 14 NB-modules, respectively. No link or offset is inserted between the NB-modules. These robots can touch their base. Figure 5.30 shows the vertical sections in $yz$-plane of the generated workspace points for the 12 NB-module robots. The workspace of the 12 NB-module robot has some internal boundaries that are bounded between $y \simeq [-0.2, 0.2]$ m and $z \simeq [0, 0.5]$ m, shown in Fig. 5.30. However, some other points are collected above and below the internal boundaries inside the workspace. These points are not part of the workspace boundaries. However, the robot NB-modules reached their limits when moving towards

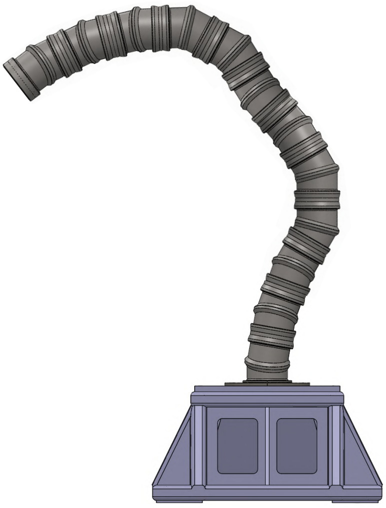


Figure 5.28: Nimbl'Bot robot composed of 12 NB-modules

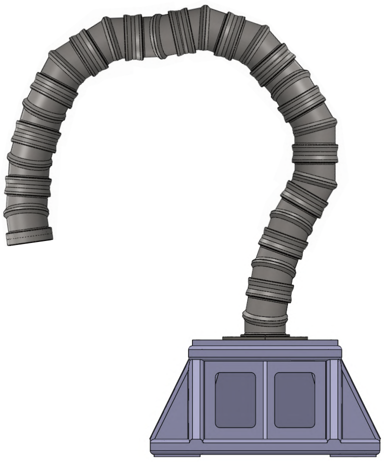


Figure 5.29: Nimbl'Bot robot composed of 14 NB-modules

these points. So, the robot was in a configuration that could not be escaped and the end-effector positions were collected as part of the boundaries. A clearer view of this behavior is shown in Fig. 5.31 for the 14 NB-module robot. It has no inner boundaries. However, several points were collected by the algorithm.

Figure 5.32 shows the 12 NB-module robot configuration to reach one of the points collected inside the workspace that are not part of the actual boundaries. The first modules of the robot reach the maximum allowed tilt and the robot can no longer move along the desired direction or escape from the singular configuration. However, the robot could reach the same end-effector linear position with another configuration and move toward it. The same behavior can be noticed for the 14 NB-module robot, as shown in Fig. 5.33. Similarly, the robot is stuck on an internal position that does not belong to the workspace boundaries. The limitation explained

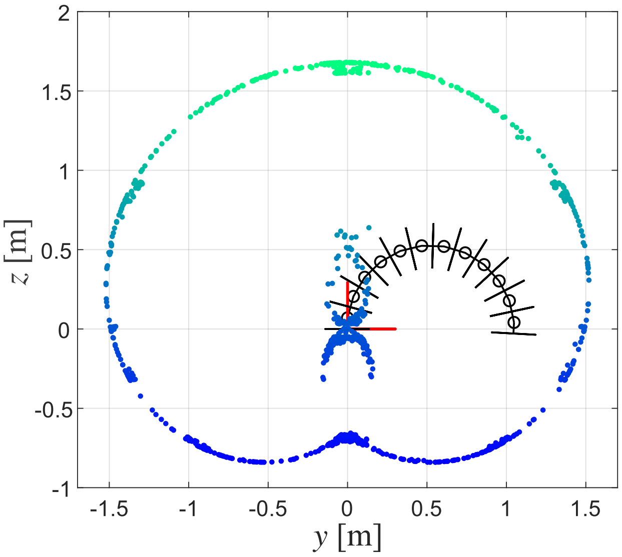


Figure 5.30: Vertical section in $yz$-plane of points describing workspace of 12 NB-module robot

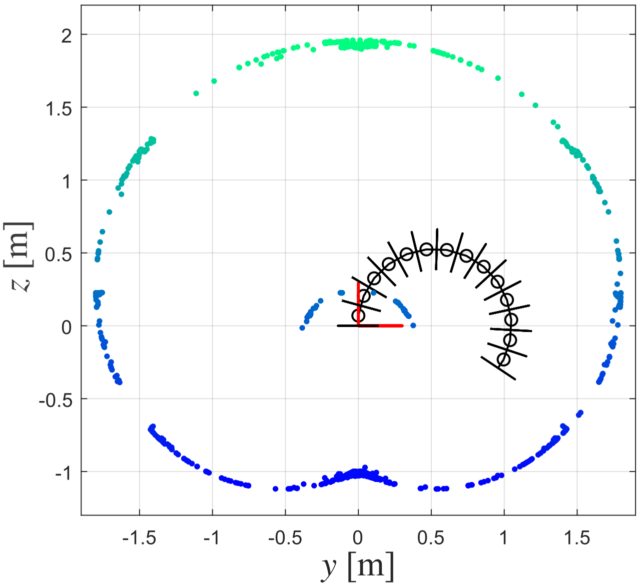


Figure 5.31: Vertical section in $yz$-plane of points describing workspace of 14 NB-module robot

in this section can generate problems in the correct identification of the manipulator workspaces. Further studies on this limitation should be done to improve the workspace determination process.

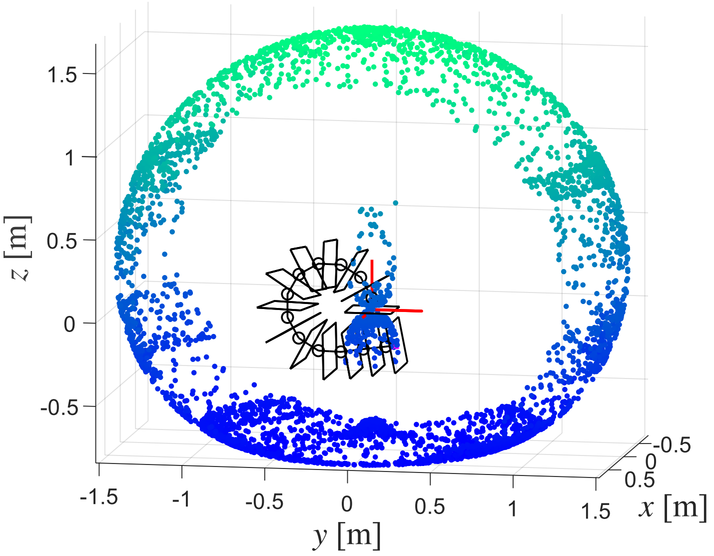


Figure 5.32: Configuration of 12 NB-module robot on point inside the workspace which does not belong to the boundaries

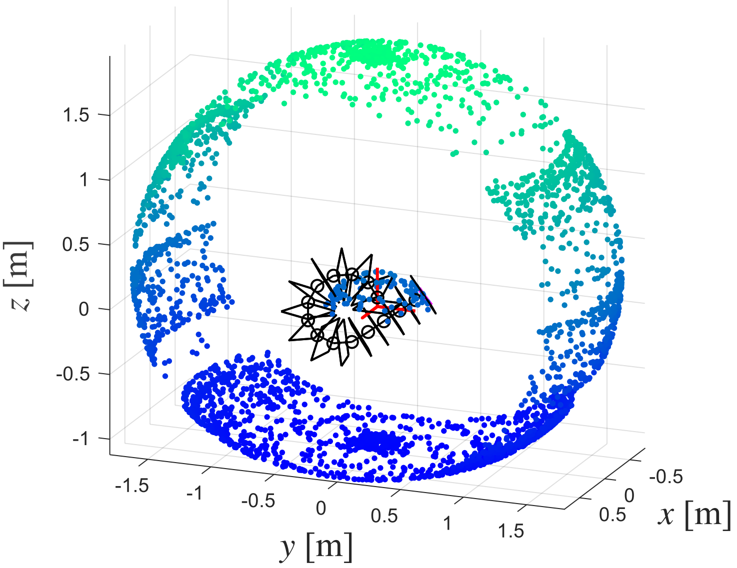


Figure 5.33: Configuration of 14 NB-module robot on point inside the workspace which does not belong to the boundaries

## 5.7 Workspace determination conclusions

This chapter presented a new algorithm for the workspace determination of robotic manipulators. The workspace determination process was evaluated on three kinematic redundant robots. However, it can also be applied to non-redundant manipulators. This process employs the TPIK algorithm and kinematic optimization tasks, namely dexterity and manipulability, for the workspace determination. It is not affected by computational redundancy, like the Monte Carlo based methods, and identifies only the workspace boundaries. The performed tests emphasized the process ability to detect the complete workspace boundaries in a small amount of time. It always took less than ten minutes to produce one workspace. The process lasted less than one minute for the smaller robot, e.g. NB-R2. Moreover, using the kinematic optimization tasks allowed for maintaining better kinematic configurations while moving and prevented the manipulator from ending in singular configurations inside the workspace. In the NB-R3 robot case, the generated map identifies the workspace inner boundaries with less accuracy. However, the workspace shape is perfectly identifiable from the obtained results. The optimized ray-based method results are compared with the ones obtained through pseudo-inverse Jacobian ray-based and Monte Carlo methods. The proposed optimized ray-based workspace determination algorithm presents more accurate results than the pseudo-inverse Jacobian ray-based method. It is also faster, more accurate and requires fewer points than the Monte Carlo one. Then, a method for interpolating the points of the NB-R1 and NB-R2 workspaces was proposed. The method can generate the surface for symmetrical workspaces. However, this process can not plot the surface for the NB-R3 workspace. The surface interpolation will be helpful to develop an algorithm to compute the reachability of a 3D point automatically. In fact, this is a complex task to automatize, although it is visually easy. Moreover, the surface generation will allow the computation of the area and volume of the workspace. Finally, two main limitation of the proposed algorithm are discussed. First, there is no prior knowledge about the analyzed robot workspaces. So, it is not possible to determine the result correctness. However, a process was explained to check the obtained results. The second limitation appears when the number of NB-modules that compose the design grows. Over 12 NB-modules, the workspace inner boundaries presents some errors because the robot remained stuck in some internal configurations. Part of the work presented in this chapter was published in [GCSL23b].

## Chapter 6

# Conclusions

Kinematic redundant manipulators are increasingly used in manufacturing industry, providing important advantages. In fact, there can be multiple possible solutions for the same task since the robot is kinematically redundant. They can work in cluttered environments with many obstacles or collaborate with humans and other robots. Moreover, redundancy can be used to solve tasks simultaneously, such as optimizing different performance indices while performing the main task. However, it is important to recognize that this kinematic redundancy also introduces complexities. The main one is the identification of an algorithm to solve the inverse kinematic model problem. Moreover, analyzing the robot features, like the workspace, and optimizing its design become more complex tasks in the presence of kinematic redundancy. This chapter gives a synopsis of the manuscript content, summarizing the main topics treated during the research, and proposes the future work for each subject.

## 6.1 Thesis synopsis

The work done in this thesis involved three main topics that are linked by two common threads. These topics are related to the problems that arise with kinematic redundant robots, especially when applied to machining applications. So, the first common thread is the use of kinematic redundant manipulators in trajectory-tracking applications. The literature on these robots is revised in the introduction and their main complexities are highlighted. In the manuscript, the kinematic redundant robot composed of the actuation mechanism developed by Nimbl'Bot is employed as example for the performed tests. This actuation mechanism is described and its geometric and kinematic models are exposed. Then, a deeper analysis of the relationship between the mechanism design parameter and its kinematic performance is proposed. The second common thread is the use of an algorithm for the kinematic redundancy resolution to identify the robot configuration for a specific task while optimizing some performance indices. In this research, a task priority based kinematic redundancy resolution algorithm was employed to kinematically control the Nimbl'Bot manipulator. It is called task priority inverse kinematic (TPIK) and exploits the robot redundancy to solve a list of prioritized tasks simultaneously.

The three main subjects that make up the thesis are briefly described below. First, the TPIK algorithm is used to kinematically control the redundant Nimbl'Bot robot following a set of desired trajectories. Since this kinematic control algorithm takes advantage of the redundancy solving simultaneous tasks, three new tasks are introduced. These tasks are based on the kinetostatic performance of the robot, namely dexterity, manipulability and robot transmission ratio (RTR). These tasks are used for the kinetostatic optimization of the robot configuration. In the conducted tests, the robot tracks different given trajectories with and without the optimization tasks. These tests are repeated several times to avoid the attractions to local maxima. The results show a better kinetostatic behavior when the optimization tasks are active. Moreover, the time difference between using or not the optimization tasks is negligible. A new index $\epsilon$ is defined as a linear combination of the kinetostatic indices and used to rate the test performance. The value of $\epsilon$ is on average 50% higher when reaching the trajectory starting poses activating the optimization tasks. The mean value of $\epsilon$ is on average 22% higher along the trajectories when the optimization tasks are active. In general, the kinetostatic performance directly relates to the trajectory placement and the velocity and force vector orientations. Finally, some studies on the linear kinematic Jacobian matrix singular vectors show that the movement effectiveness along the direction $\vec{y}$ is reduced compared to the other axes.

The second topic proposes a method for the design optimization of kinematic redundant robots. Here, the TPIK algorithm is employed to create this novel approach and optimize the design with respect to the desired applications and the kinetostatic indices dexterity, manipulability and RTR. This process considers the optimized design parameters as controllable virtual joints and updates their values while moving the robot. Initially, a simpler case is used to validate the new approach. Only two design variables and two paths are used and the results are compared with a discretized method. The two methods converged to equivalent results, obtaining the same performance, but the new process proposed here requires six time less the total computational time. In fact, the proposed optimization process can identify the best solution for a specific application without testing all the possible design parameter combinations. Later, the proposed method is applied to a case study with more design parameters and trajectories. Several possible Nimbl'Bot robot designs are identified with high kinetostatic performance in the desired workspace area. The algorithm is tested with and without a task based on the center of mass to compare the ending robot dimension difference. When the center of mass task is not used, the resulting designs have high kinetostatic performance but too large dimensions for a real application. When the center of mass task is employed, the obtained designs are smaller, generating some realizable manipulators, but the kinetostatic performance is lower than in the previous case. In conclusion, this design optimization algorithm gives the guidelines for building a performant redundant robot based on a desired application and some performance metrics. Of course, some rate parameters can be antagonistic or not comparable to each other, like the kinetostatic indices and the center of mass distance. So, the user will have to use the guidelines to choose the most suitable result, doing a trade-off between all the application requirements.

The third topic is related to the kinematic redundant robot workspace determination and analysis. The workspace determination process is developed and evaluated on some kinematic redundant designs and employs a ray-based concept. However, it can also be applied to non-redundant manipulators. This process employs the TPIK algorithm and kinematic optimization tasks, namely dexterity and manipulability, for the workspace determination. The goal is to identify the workspace boundaries in a shorter period of time, avoiding the problems that Monte Carlo based methods have facing with. The tests are performed on three Nimbl'Bot designs and the results give a clear map of the workspaces. Each test takes less than ten minutes to produce one workspace and less than one minute for the smaller robot. In the case of robots with non-symmetrical workspaces, the workspace inner boundary profiles are less accurate than in the cases of symmetrical workspaces. Nevertheless, the resulting workspace shape can still be accurately determined based on the outcomes. The optimized ray-based method is compared two other methods, pseudo-inverse Jacobian ray-based and Monte Carlo. The proposed algorithm presents more accurate results than the pseudo-inverse Jacobian ray-based method. It is also faster, more accurate and requires fewer points than the Monte Carlo one. Then, a new point interpolating method for the symmetrical workspaces is introduced to plot the workspace surfaces. The surface generation is helpful to understand more features of the workspace, like calculating its volume or computing the reachability of a 3D point. Two main limitation of the proposed algorithm are discussed. First, there is no prior knowledge about the analyzed robot workspaces. So, it is not possible to determine the result correctness. However, a process was explained to check the obtained results. The second limitation appears when the number of NB-modules that compose the design grows. Over 12 NB-modules, the workspace inner boundaries presents some errors because the robot remained stuck in some internal configurations.

All the proposed algorithms were tested on several different Nimbl'Bot robotic designs built through a serial connection of the NB-modules. However, these methods can be applied to any type of kinematic redundant manipulator. All the proposed algorithms give promising results and could be further fine-tuned to improve the resulting quality.

## 6.2 Future work

The work done in this thesis spreads in different fields and opens other subjects. This section presents the future work and analysis for each topic treated in this research.

1. **NB-module Modeling and Analysis:** Starting from Chapter 2, the NB-module geometric and kinematic models were described and analyzed. However, its dynamic model was not treated in this research. Similarly, the stiffness of the NB-module was not modeled. Future analyses should address these topics, which are relevant to demonstrate the abilities and limits of the robots actuated by NB-modules.

2. **Task Priority Kinematic Control:** The robot kinetostatic performance was tested by tracking some trajectories in Chapter 3. However, the proposed study uses only four squared trajectories with constant velocities and forces to test the robot performance. So, it is impossible to identify the best placement and orientation for the workpiece. This concept is the starting point for future analysis. Then, the performance of other existing manipulators should be compared with the Nimbl'Bot design one on the same tasks. This comparison should be made later on to present the Nimbl'Bot design potentials with respect to the counterparts. Moreover, the simulation tests could include some obstacles and self-collision avoidance tasks. These tasks allow the robot to work in more complex environments or with other robots. Finally, all the tests were performed in simulation. The TPIK algorithm should be tested on a real prototype of the Nimbl'Bot robot to demonstrate its abilities in real scenarios.

3. **Design Optimization Process:** In Chapter 4, the proposed design optimization process provided guidelines to build kinetostatic optimized Nimbl'Bot designs with respect to the desired machining application. Future work could involve further analysis to identify if more general guidelines exist for building a Nimbl'Bot robot design with high kinetostatic performance. For example, this could be done by giving more importance to one index than others or searching for specific relationships between the design parameters. Other design parameters could be included to study how they affect the kinetostatic performance. Moreover, obstacle and self-collision avoidance could be added to the optimization process to consider a more complex environment.

4. **Workspace Determination Algorithm:** Regarding the workspace determination algorithm proposed in Chapter 5, the process needs to be revised to improve the non-symmetrical workspace identification. Future work could also address the workspace determination for a specific end-effector orientation. This is important when planning the workpiece placement inside the robot reachable area. Then, a general process to interpolate the workspace points for any robot should be developed, starting from the one already proposed for symmetrical workspaces. So, it should be possible to plot the workspace surface for any Nimbl'Bot design and automatically compute whether a point is inside the workspace. Finally, some additional steps should be added to the workspace determination process to escape the inner boundary identification problem.

# Bibliography

[ABR08] Gabriella Acaccia, Luca Bruzzone, and Roberto Razzoli. A modular robotic system for industrial applications. *Assembly Automation*, 28(2):151–162, 2008.

[ADJM13] Hatem Al-Dois, AK Jha, and RB Mishra. Task-based design optimization of serial robot manipulators. *Engineering Optimization*, 45(6):647–658, 2013.

[AEL19] Ghasem Abbasnejad, Jonathan Eden, and Darwin Lau. Generalized ray-based lattice generation and graph representation of wrench-closure workspace for arbitrary cable-driven robots. *IEEE Transactions on Robotics*, 35(1):147–161, 2019.

[ALC92] Jorge Angeles and Carlos S López-Cajún. Kinematic isotropy and the conditioning index of serial robotic manipulators. *The International Journal of Robotics Research*, 11(6):560–571, 1992.

[AM15] Hossein Ahmadzadeh and Ellips Masehian. Modular robotic systems: Methods and algorithms for abstraction, planning, control, and synchronization. *Artificial Intelligence*, 223:27–64, 2015.

[Ang92] Jorge Angeles. The design of isotropic manipulator architectures in the presence of redundancies. *The International Journal of Robotics Research*, 11(3):196–201, 1992.

[Ang03] Jorge Angeles. *Fundamentals of robotic mechanical systems: theory, methods, and algorithms.* Springer, 2003.

[APS19] Reem J Alattas, Sarosh Patel, and Tarek M Sobh. Evolutionary modular robotics: Survey and analysis. *Journal of Intelligent & Robotic Systems*, 95:815–828, 2019.

[BKRC15] Jessica Burgner-Kahrs, D Caleb Rucker, and Howie Choset. Continuum robots for medical applications: A survey. *IEEE Transactions on Robotics*, 31(6):1261–1280, 2015.

[BMR12] Oriol Bohigas, Montserrat Manubens, and Lluís Ros. A complete method for workspace boundary determination on general structure manipulators. *IEEE Transactions on Robotics*, 28(5):993–1006, 2012.

[Bra16] Mathias Brandstötter. *Adaptable serial manipulators in modular design*. PhD thesis, UMIT, Institute of Automation andControl Engineering, Hall in Tirol, Austria, 2016.

[BRS$^+$17] Alberto Brunete, Avinash Ranganath, Sergio Segovia, Javier Perez De Frutos, Miguel Hernando, and Ernesto Gambao. Current trends in reconfigurable modular robots design. *International Journal of Advanced Robotic Systems*, 14(3):1729881417710457, 2017.

[BZG02] IA Bonev, D Zlatanov, and CM Gosselin. Advantages of the modified Euler angles in the design and control of PKMs. In *Proceedings of Parallel Kinematic Machines International Conference*, pages 171–188, Quebec, Canada, September 29–October 2 2002. Citeseer.

[BZL89] Beno Benhabib, G Zak, and MG Lipton. A generalized kinematic modeling method for modular robots. *Journal of robotic systems*, 6(5):545–571, 1989.

[Car09] Marco Carricato. Decoupled and homokinetic transmission of rotational motion via constant-velocity joints in closed-chain orientational manipulators. *Journal of Mechanisms and Robotics*, 1(4):041008, 2009.

[CB92] Gregory S Chirikjian and Joel W Burdick. A geometric approach to hyper-redundant manipulator obstacle avoidance. *Journal of Mechanical Design*, 114(4):580–585, 1992.

[CB93] Gregory S Chirikjian and Joel W Burdick. Design and experiments with a 30 dof robot. In *Proceedings of International Conference on Robotics and Automation*, pages 113–119, Atlanta, GA, May 02–06 1993. IEEE.

[CB94] Gregory S Chirikjian and Joel W Burdick. A hyper-redundant manipulator. *IEEE Robotics & Automation Magazine*, 1(4):22–29, 1994.

[CB95] Gregory S Chirikjian and Joel W Burdick. Kinematically optimal hyper-redundant manipulator configurations. *IEEE transactions on Robotics and Automation*, 11(6):794–806, 1995.

[CBH08] Alexandre Campos, Christoph Budde, and Jürgen Hesselbach. A type synthesis method for hybrid robot structures. *Mechanism and Machine Theory*, 43(8):984–995, 2008.

[CCRC18] Marco Ceccarelli, Daniele Cafolla, Matteo Russo, and Giuseppe Carbone. Heritagebot platform for service in cultural heritage frames. *International Journal of Advanced Robotic Systems*, 15(4):1729881418790692, 2018.

[CDGF13] Stéphane Caro, Claire Dumas, Sébastien Garnier, and Benoît Furet. Workpiece placement optimization for machining operations with a KUKA KR270-2 robot. In *Proceedings of International Conference on Robotics and Automation*, pages 2921–2926, Karlsruhe, Germany, May 6-10 2013. IEEE.

[CGSBK18] Mohamed Taha Chikhaoui, Josephine Granna, Julia Starke, and Jessica Burgner-Kahrs. Toward motion coordination control and design optimization for dual-arm concentric tube continuum robots. *IEEE Robotics and Automation Letters*, 3(3):1793–1800, 2018.

[Che08] Kai Cheng. *Machining dynamics: fundamentals, applications and practices*. Springer Science & Business Media, 2008.

[CL22] Hung Hon Cheng and Darwin Lau. Ray-based cable and obstacle interference-free workspace for cable-driven parallel robots. *Mechanism and Machine Theory*, 172:104782, 2022.

[CLV06] S-H Cha, TA Lasky, and SA Velinsky. Kinematic redundancy resolution for serial-parallel manipulators via local optimization including joint constraints. *Mechanics based design of structures and machines*, 34(2):213–239, 2006.

[COW08] Stefano Chiaverini, Giuseppe Oriolo, and Ian D. Walker. *Kinematically Redundant Manipulators*, pages 245–268. Springer Berlin Heidelberg, 2008.

[CWCC16] Daniele Cafolla, Mingfeng Wang, Giuseppe Carbone, and Marco Ceccarelli. Larmbot: a new humanoid robot with parallel mechanisms. In

*ROMANSY 21-Robot Design, Dynamics and Control: Proceedings of the 21st CISM-IFToMM Symposium*, pages 275–283. Springer, 2016.

[CY96] I-Ming Chen and Guilin Yang. Configuration independent kinematics for modular robots. In *Proceedings of International Conference on Robotics and Automation*, volume 2, pages 1440–1445, Minneapolis, MN, April 22–28 1996. IEEE.

[DBG$^+$19] Dhaivat Dholakiya, Shounak Bhattacharya, Ajay Gunalan, Abhik Singla, Shalabh Bhatnagar, Bharadwaj Amrutur, Ashitava Ghosal, and Shishir Kolathaya. Design, development and experimental realization of a quadrupedal research platform: Stoch. In *Proceedings of 5th International Conference on Control, Automation and Robotics*, pages 229–234, Beijing, China, April 19–22 2019. IEEE.

[DCGF12] Claire Dumas, Stéphane Caro, Stéphane Garnier, and Benoît Furet. Workpiece Placement Optimization of Six-Revolute Industrial Serial Robots for Machining Operations. *Proceedings of 11th Biennial Conference on Engineering Systems Design and Analysis*, 2:419–428, July 2–4 2012.

[DDC13] Hui Dong, Zhijiang Du, and Gregory S Chirikjian. Workspace density and inverse kinematics for planar serial revolute manipulators. *Mechanism and Machine Theory*, 70:508–522, 2013.

[DDN19] Ayan Dutta, Prithviraj Dasgupta, and Carl Nelson. Distributed configuration formation with modular robots using (sub) graph isomorphism-based approach. *Autonomous Robots*, 43:837–857, 2019.

[DFDC15] Hui Dong, Taosha Fan, Zhijiang Du, and Gregory S Chirikjian. Inverse kinematics of discretely actuated ball-joint manipulators using workspace density. In *Proceedings of International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, volume 57144, page V05CT08A039, Boston, MA, August 2–5 2015. American Society of Mechanical Engineers.

[DK04] Etienne Dombre and Wisama Khalil. *Modeling, identification and control of robots.* Butterworth-Heinemann, (2004).

[DLCA19] Paolo Di Lillo, Stefano Chiaverini, and Gianluca Antonelli. Handling robot constraints within a set-based multi-task priority inverse kinematics framework. In *Proceedings of International Conference on Robotics and Automation*, pages 7477–7483, Montreal, Canada, May 20–24 2019. IEEE.

[DOXY20] Zhao-cai Du, Guang-Yao Ouyang, Jun Xue, and Yan-bin Yao. A review on kinematic, workspace, trajectory planning and path planning of hyper-redundant manipulators. In *Proceedings of 10th Institute of Electrical and Electronics Engineers International Conference on Cyber Technology in Automation, Control, and Intelligent Systems*, pages 444–449, Xi'an, China, October 10–13 2020. IEEE.

[DP14] Vladimir Dukovski and Zoran Pandilov. Comparison of the characteristics between serial and parallel robots. *Acta Technica Corvininesis-Bulletin of Engineering*, 7(1), 2014.

[Duf21] Ludovic Dufau. Articulated robot arm. US patent 10,953,554 `https://uspto.report/patent/grant/10,953,554`, March 23, 2021. Online accessed 23 January 2023.

[EMW14] Adrien Escande, Nicolas Mansard, and Pierre-Brice Wieber. Hierarchical quadratic programming: Fast online humanoid-robot motion generation. *The International Journal of Robotics Research*, 33(7):1006–1028, 2014.

[EWO+14] Johannes Englsberger, Alexander Werner, Christian Ott, Bernd Henze, Maximo A Roa, Gianluca Garofalo, Robert Burger, Alexander Beyer, Oliver Eiberger, Korbinian Schmid, et al. Overview of the torque-controlled humanoid robot toro. In *Proceedings of International Conference on Humanoid Robots*, pages 916–923, Madrid, Spain, November 18–20 2014. IEEE-RAS.

[FDL13] Fabrizio Flacco and Alessandro De Luca. Optimal redundancy resolution with task scaling under hard bounds in the robot joint space. In *Proceedings of International Conference on Robotics and Automation*, pages 3969–3975, Karlsruhe, Germany, May 06–10 2013. IEEE.

[FDL14] Fabrizio Flacco and Alessandro De Luca. A reverse priority approach to multi-task control of redundant robots. In *Proceedings of International Conference on Intelligent Robots and Systems*, pages 2421–2427, Chicago, IL, September 14–18 2014. IEEE.

[FDLK12] Fabrizio Flacco, Alessandro De Luca, and Oussama Khatib. Prioritized multi-task motion control of redundant robots under hard joint constraints. In *Proceedings of International Conference on Intelligent Robots and Systems*, pages 3970–3977, Vilamoura-Algarve, Portugal, October 7–12 2012. IEEE.

[FK90] Toshio Fukuda and Yoshio Kawauchi. Cellular robotic system (cebot) as one of the realization of self-organizing intelligent universal manipulator. In *Proceedings of International Conference on Robotics and Automation*, pages 662–667, Cincinnati, OH, May 13–18 1990. IEEE.

[FN88] Toshio Fukuda and Seiya Nakagawa. Approach to the dynamically reconfigurable robotic system. *Journal of Intelligent and Robotic Systems*, 1:55–72, 1988.

[FSMVM$^+$13] Alfonso Fernández-Sarría, Lucía Martínez, Borja Velázquez-Martí, Magdalena Sajdak, J Estornell, and JA Recio. Different methodologies for calculating crown volumes of platanus hispanica trees using terrestrial laser scanner and a comparison with classical dendrometric measurements. *Computers and electronics in agriculture*, 90:176–185, 2013.

[GA91] Clement Gosselin and Jorge Angeles. A global performance index for the kinematic optimization of robotic manipulators. *Journal of Mechanical Design*, 113(3):220–226, 1991.

[GCSL23a] Angelica Ginnante, Stéphane Caro, Enrico Simetti, and François Leborne. Kinetostatic optimization for kinematic redundancy planning of nimbl'bot robot. *Journal of Mechanisms and Robotics*, 16(3), 2023.

[GCSL23b] Angelica Ginnante, Stéphane Caro, Enrico Simetti, and François Leborne. Workspace determination of kinematic redundant manipulators using a ray-based method. In *Proceedings of International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Boston, Massachusetts, August 20–23 2023. American Society of Mechanical Engineers.

[GKY18] Kevin G Gim, Joohyung Kim, and Katsu Yamane. Design and fabrication of a bipedal robot using serial-parallel hybrid leg mechanism.

In *Proceedings of International Conference on Intelligent Robots and Systems*, pages 5095–5100, Madrid, Spain, October 1–5 2018. IEEE.

[GLC+21] Angelica Ginnante, François Leborne, Stéphane Caro, Enrico Simetti, and Giuseppe Casalino. Design and kinematic analysis of a novel 2-dof closed-loop mechanism for the actuation of machining robots. In *Proceedings of International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, volume 85444, Online, Virtual, August 17–19 2021. American Society of Mechanical Engineers.

[GP73] Gene H Golub and Victor Pereyra. The differentiation of pseudo-inverses and nonlinear least squares problems whose variables separate. *SIAM Journal on numerical analysis*, 10(2):413–432, 1973.

[GS18] Clément Gosselin and Louis-Thomas Schreiber. Redundancy in parallel mechanisms: A review. *Applied Mechanics Reviews*, 70(1):010802, 2018.

[GSCL23] Angelica Ginnante, Enrico Simetti, Stéphane Caro, and François Leborne. Task priority based design optimization of a kinematic redundant robot. *Mechanism and Machine Theory*, 187:105374, 2023.

[GST19] Bora Gonul, Omer Faruk Sapmaz, and Lutfi Taner Tunc. Improved stable conditions in robotic milling by kinematic redundancy. *Procedia CIRP*, 82:485–490, 2019.

[GW00] Ian A Gravagne and Ian D Walker. On the structure of minimum effort solutions with application to kinematic redundancy resolution. *IEEE Transactions on Robotics and Automation*, 16(6):855–863, 2000.

[GY06] Yisheng Guan and Kazuhito Yokoi. Reachable space generation of a humanoid robot using the monte carlo method. In *Proceedings of International Conference on Intelligent Robots and Systems*, pages 1984–1989, Beijing, China, October 09–15 2006. IEEE.

[HKC+17] Soonwoong Hwang, Hyeonguk Kim, Younsung Choi, Kyoosik Shin, and Changsoo Han. Design optimization method for 7 dof robot manipulator using performance indices. *International Journal of Precision Engineering and Manufacturing*, 18(3):293–299, 2017.

[HN91] Peter Hughes and Frank Naccarato. Inverse kinematics of variable geometry truss manipulators. *Journal of Robotic Systems*, 8(2):249–266, 1991.

[HPX+21] Yiheng Han, Jia Pan, Mengfei Xia, Long Zeng, and Yong-Jin Liu. Efficient se (3) reachability map generation via interplanar integration of intra-planar convolutions. In *Proceedings of International Conference on Robotics and Automation*, pages 1854–1860, Xi'an China, May 30–June 5 2021. IEEE.

[HW03] Michael W Hannan and Ian D Walker. Kinematics and the implementation of an elephant's trunk manipulator and other continuum style robots. *Journal of robotic systems*, 20(2):45–63, 2003.

[ISA15] I Iglesias, MA Sebastián, and JE Ares. Overview of the state of robotic machining: Current situation and future potential. *Procedia engineering*, 132:911–917, 2015.

[JLKH19] Dominic Jud, Philipp Leemann, Simon Kerscher, and Marco Hutter. Autonomous free-form trenching using a walking excavator. *IEEE Robotics and Automation Letters*, 4(4):3208–3215, 2019.

[JW19] Wei Ji and Lihui Wang. Industrial robotic machining: a review. *The International Journal of Advanced manufacturing Technology*, 103(1-4):1239–1255, 2019.

[JWT+11] Aaron Johnson, Cornell Wright, Matthew Tesch, Kevin Lipkin, and Howie Choset. A novel architecture for modular snake robots. *Citeseer, Tech. Rep.*, 2011.

[KA05] Waseem A Khan and Jorge Angeles. The kinetostatic optimization of robotic manipulators: The inverse and the direct problems. *Journal of Mechanical Design*, 128(1):168–178, 2005.

[KAW15] Suleman Khan, Kjell Andersson, and Jan Wikander. Jacobian matrix normalization - A comparison of different approaches in the context of multi-objective optimization of 6-dof haptic devices. *Journal of Intelligent & Robotic Systems*, 79(1):87–100, 2015.

[KK93] J-O Kim and Pradeep K Khosla. A formulation for task based design of robot manipulators. In *Proceedings of RSJ International Confer-*

*ence on Intelligent Robots and Systems*, volume 3, pages 2310–2317, Yokohama, Japan, July 26–30 1993. IEEE.

[KNH+19] Seong Hyeon Kim, Eunseok Nam, Tae In Ha, Soon-Hong Hwang, Jae Ho Lee, Soo-Hyun Park, and Byung-Kwon Min. Robotic machining: A review of recent progress. *International Journal of Precision Engineering and Manufacturing*, 20:1629–1642, 2019.

[KSP17] Sorada Khaengkam, Jiraphon Srisertpol, and Veerawuth Punlum. The application of double arms scara robot for deburring of pcb support plate. In *Proceedings of International Conference on Circuits, Devices and Systems*, pages 1–5, Chengdu, China, September 05–08 2017. IEEE.

[KSR+14] Virendra Kumar, Soumen Sen, Shibendu S Roy, Chandan Har, and SN Shome. Design optimization of serial link redundant manipulator: an approach using global performance metric. *Procedia Technology*, 14:43–50, 2014.

[KTV+90] James P Karlen, Jack M Thompson, Havard I Vold, James D Farrell, and Paul H Eismann. A dual-arm dexterous manipulator system with anthropomorphic kinematics. In *Proceedings of International Conference on Robotics and Automation*, pages 368–373, Cincinnati, OH, May 13–18 1990. IEEE.

[KWdGF+20] Shivesh Kumar, Hendrik Wöhrle, José de Gea Fernández, Andreas Müller, and Frank Kirchner. A survey on modularity and distributivity in series-parallel hybrid robots. *Mechatronics*, 68:102367, 2020.

[LBUP06] Sebastian Lohmeier, Thomas Buschmann, Heinz Ulbrich, and Friedrich Pfeiffer. Modular joint design for performance enhanced humanoid robot lola. In *Proceedings of International Conference on Robotics and Automation*, pages 88–93, Orlando, FL, May 15–19 2006. IEEE.

[LPSG13] Pål Liljebäck, Kristin Y Pettersen, Øyvind Stavdahl, and Jan Tommy Gravdahl. *Snake robots: modelling, mechatronics, and control.* Springer, 2013.

[LSFY18] Li Li, Junyun Shang, YL Feng, and Huai Yawen. Research of trajectory planning for articulated industrial robot: a review. *Computer engineering and applications*, 54(5):36–50, 2018.

[LUE90] Li Liu, BJ Ulrich, and Mohamed A Elbestawi. Robotic grinding force regulation: design, implementation and benefits. In *Proceedings of International Conference on Robotics and Automation*, pages 258–265, Cincinnati, OH, May 13–18 1990. IEEE.

[LXGC17] Yiming Liu, Hui Xu, Changxing Geng, and Guodong Chen. A modular manipulator for industrial applications: Design and implement. In *Proceedings of 2nd International Conference on Robotics and Automation Engineering*, pages 331–335, Shanghai, China, December 29–31 2017. IEEE.

[MD95] Hamid Reza Mohammadi Daniali. *Contributions to the kinematic synthesis of parallel manipulators*. PhD thesis, McGill University, Canada, 1995.

[MDA22] Omar W Maaroof, Mehmet İsmet Can Dede, and Levent Aydin. A robot arm design optimization method by using a kinematic redundancy resolution technique. *Robotics*, 11(1):1, 2022.

[Mer06] Jean-Pierre Merlet. *Parallel robots*, volume 128. Springer Science & Business Media, 2006.

[MKYC02] Giacomo Marani, Jinhyun Kim, Junku Yuh, and Wan Kyun Chung. A real-time approach for singularity avoidance in resolved motion rate control of robotic manipulators. In *Proceedings of International Conference on Robotics and Automation*, volume 2, pages 1973–1978, Washington, DC, May 11–15 2002. IEEE.

[MRG17] Midhun S Menon, VC Ravi, and Ashitava Ghosal. Trajectory planning and obstacle avoidance for hyper-redundant serial robots. *Journal of Mechanisms and Robotics*, 9(4), 2017.

[NCW18] Abhilash Nayak, Stéphane Caro, and Philippe Wenger. Comparison of 3-[pp] s parallel manipulators based on their singularity free orientation workspace, parasitic motions and complexity. *Mechanism and Machine Theory*, 129:293–315, 2018.

[NHY87] Yoshihiko Nakamura, Hideo Hanafusa, and Tsuneo Yoshikawa. Task-priority based redundancy control of robot manipulators. *The International Journal of Robotics Research*, 6(2):3–15, 1987.

[NPRRA02] J Norberto Pires, John Ramming, Stephen Rauch, and Ricardo Araújo. Force/torque sensing applied to industrial robotic deburring. *Sensor Review*, 22(3):232–241, 2002.

[ODAS15] Christian Ott, Alexander Dietrich, and Alin Albu-Schäffer. Prioritized multi-task compliance control of redundant manipulators. *Automatica*, 53:416–423, 2015.

[OHAH+20] Olatunji Mumini Omisore, Shipeng Han, Yousef Al-Handarish, Wenjing Du, Wenke Duan, Toluwanimi Oluwadara Akinyemi, and Lei Wang. Motion and trajectory constraints control modeling for flexible surgical robotic systems. *Micromachines*, 11(4):386, 2020.

[Par00] Jonghoon Park. Analysis and control of kinematically redundant manipulators: An approach based on kinematically decoupled joint space decomposition. *PhD Thesis, POSTECH*, 2000.

[PC06] Geoffrey Pond and Juan A Carretero. Formulating jacobian matrices for the dexterity analysis of parallel manipulators. *Mechanism and Machine Theory*, 41(12):1505–1519, 2006.

[PCY03] Joon-Young Park, Pyung-Hun Chang, and Jeong-Yean Yang. Task-oriented design of robot kinematics using the grid method. *Advanced robotics*, 17(9):879–907, 2003.

[PDSC11] John Pandremenos, Christos Doukas, Panagiotis Stavropoulos, and George Chryssolouris. Machining with robots: a critical review. pages 1–9, Athens, Greece, September 28–30 2011.

[Pet17] Kristin Y Pettersen. Snake robots. *Annual Reviews in Control*, 44:19–44, 2017.

[PK93] Christiaan JJ Paredis and Pradeep K Khosla. Kinematic design of serial link manipulators from task specifications. *The International Journal of Robotics Research*, 12(3):274–287, 1993.

[PRG+17] Adrián Peidró, Óscar Reinoso, Arturo Gil, José María Marín, and Luis Payá. An improved monte carlo method based on gaussian growth to calculate the workspace of robots. *Engineering Applications of Artificial Intelligence*, 64:197–207, 2017.

[PSVP13] Doina Pisla, Andras Szilaghyi, Calin Vaida, and Nicolae Plitea. Kinematics and workspace modeling of a new hybrid robot used in minimally invasive surgery. *Robotics and Computer-Integrated Manufacturing*, 29(2):463–474, 2013.

[RCC08] Novona Rakotomanga, Damien Chablat, and Stéphane Caro. Kinetostatic performance of a planar parallel mechanism with variable actuation. In *Advances in robot kinematics: Analysis and design*, pages 311–320. Springer, 2008.

[RMG16] Alexander Reiter, Andreas Müller, and Hubert Gattringer. Inverse kinematics in minimum-time trajectory planning for kinematically redundant manipulators. In *IECON 2016-42nd Annual Conference of the IEEE Industrial Electronics Society*, pages 6873–6878, Florence, Italy, October 23–26 2016. IEEE.

[RSBT18] William S Rone, Wael Saab, and Pinhas Ben-Tzvi. Design, modeling, and integration of a flexible universal spatial robotic tail. *Journal of Mechanisms and Robotics*, 10(4):041001, 2018.

[RSH$^+$15] Nicolaus A Radford, Philip Strawser, Kimberly Hambuchen, Joshua S Mehling, William K Verdeyen, A Stuart Donnan, James Holley, Jairo Sanchez, Vienny Nguyen, Lyndon Bridgwater, et al. Valkyrie: Nasa's first bipedal humanoid robot. *Journal of Field Robotics*, 32(3):397–419, 2015.

[SAM$^+$17] Filippo Sanfilippo, Jon Azpiazu, Giancarlo Marafioti, Aksel A Transeth, Øyvind Stavdahl, and Pål Liljebäck. Perception-driven obstacle-aided locomotion for snake robots: the state of the art, challenges and possibilities. *Applied Sciences*, 7(4):336, 2017.

[SC16] Enrico Simetti and Giuseppe Casalino. A novel practical technique to integrate inequality control objectives and task transitions in priority based control. *Journal of Intelligent & Robotic Systems*, 84(1-4):877–902, 2016.

[SCWA18] Enrico Simetti, Giuseppe Casalino, Francesco Wanderlingh, and Michele Aicardi. Task priority control of underwater intervention systems: Theory and applications. *Ocean Engineering*, 164:40–54, 2018.

[SCWA19] Enrico Simetti, Giuseppe Casalino, Francesco Wanderlingh, and Michele Aicardi. A task priority approach to cooperative mobile manipulation: Theory and experiments. *Robotics and Autonomous Systems*, 122:103287, 2019.

[Sic90] Bruno Siciliano. Kinematic control of redundant robot manipulators: A tutorial. *Journal of intelligent and robotic systems*, 3(3):201–212, 1990.

[SK05] Luis Sentis and Oussama Khatib. Synthesis of whole-body behaviors through hierarchical control of behavioral primitives. *International Journal of Humanoid Robotics*, 2(04):505–518, 2005.

[SKK08] Bruno Siciliano, Oussama Khatib, and Torsten Kröger. *Redundant robots*, volume 200. Springer, 2008.

[SNM$^+$17] Steffen Schütz, Atabak Nejadfard, Krzysztof Mianowski, Patrick Vonwirth, and Karsten Berns. Carl—a compliant robotic leg featuring mono-and biarticular actuation. In *Proceedings of 17th International Conference on Humanoid Robotics*, pages 289–296, Birmingham, UK, November 15–17 2017. IEEE-RAS.

[SS91] B Siciliano and J-J E Slotine. A general framework for managing multiple tasks in highly redundant robotic systems. In *Proceeding of 5th International Conference on Advanced Robotics*, volume 2, pages 1211–1216, Seattle, WA, July 18–20 1991.

[SW95] Sanjeev Seereeram and John T Wen. A global approach to path planning for redundant manipulators. *IEEE Transactions on Robotics and Automation*, 11(1):152–160, 1995.

[SWBC03] Elie Shammas, Alon Wolf, H Ben Brown, and Howie Choset. New joint design for three-dimensional hyper redundant robots. In *Proceedings of RSJ International Conference on Intelligent Robots and Systems*, volume 4, pages 3594–3599, Las Vegas, NV, October 27–31 2003. IEEE.

[SWC06] Elie Shammas, Alon Wolf, and Howie Choset. Three degrees-of-freedom joint for spatial hyper-redundant robots. *Mechanism and machine theory*, 41(2):170–190, 2006.

[SY11] Lin Song and Suixian Yang. Research on modular design of perpendicular jointed industrial robots. In *Proceedings of Intelligent Robotics and Applications: 4th International Conference*, pages 63–72, Aachen, Germany, December 6–8 2011. Springer.

[Tan00] Tanio K Tanev. Kinematics of a hybrid (parallel–serial) robot manipulator. *Mechanism and Machine Theory*, 35(9):1183–1196, 2000.

[TGA93] Yoshimi Takeuchi, Dongfang Ge, and Naoki Asakawa. Automated polishing process with a human-like dexterous robot. In *Proceedings of International Conference on Robotics and Automation*, pages 950–956, Atlanta, GA, May 02–06 1993. IEEE.

[TGK99] HK Tönshoff, H Grendel, and R Kaak. Structure and characteristics of the hybrid manipulator georg v. In *Parallel Kinematic Machines: Theoretical Aspects and Industrial Requirements*, pages 365–376. Springer, 1999.

[WBB+12] Cornell Wright, Austin Buchan, Ben Brown, Jason Geist, Michael Schwerin, David Rollinson, Matthew Tesch, and Howie Choset. Design and architecture of the unified modular snake robot. In *Proceedings of IEEE International Conference on Robotics and Automation*, pages 4347–4354, Saint Paul, MN, çqy 14–18 2012. IEEE.

[WBC+03] Alon Wolf, H Benjamin Brown, Randy Casciola, Albert Costa, Michael Schwerin, E Shamas, and Howie Choset. A mobile hyper redundant mechanism for search and rescue tasks. In *Proceedings of RSJ International Conference on Intelligent Robots and Systems*, volume 3, pages 2889–2895, Las Vegas, NV, October 27–31 2003. IEEE.

[WC04] Yunfeng Wang and Gregory S Chirikjian. Workspace generation of hyper-redundant manipulators as a diffusion process on se (n). *IEEE Transactions on Robotics and Automation*, 20(3):399–408, 2004.

[WC18] Julian Whitman and Howie Choset. Task-specific manipulator design and trajectory synthesis. *IEEE Robotics and Automation Letters*, 4(2):301–308, 2018.

[WJP+07] Cornell Wright, Aaron Johnson, Aaron Peck, Zachary McCord, Allison Naaktgeboren, Philip Gianfortoni, Manuel Gonzalez-Rivero, Ross

Hatton, and Howie Choset. Design of a modular snake robot. In *Proceedings of International Conference on Intelligent Robots and Systems*, pages 2609–2614, San Diego, CA, October 29–November 02 2007. IEEE.

[WWS$^+$17] Patrick M Wensing, Albert Wang, Sangok Seok, David Otten, Jeffrey Lang, and Sangbae Kim. Proprioceptive actuator design in the mit cheetah: Impact mitigation and high-bandwidth physical interaction for dynamic legged robots. *Ieee transactions on robotics*, 33(3):509–522, 2017.

[YMM11] Samer Yahya, Mahmoud Moghavvemi, and Haider AF Mohamed. Geometrical approach of planar hyper-redundant manipulators: Inverse kinematics, path planning and workspace. *Simulation Modelling Practice and Theory*, 19(1):406–422, 2011.

[Yos85] Tsuneo Yoshikawa. Manipulability of robotic mechanisms. *The international journal of Robotics Research*, 4(2):3–9, 1985.

[ZCL20] Zeqing Zhang, Hung Hon Cheng, and Darwin Lau. Efficient wrench-closure and interference-free conditions verification for cable-driven parallel robot trajectories using a ray-based method. *IEEE Robotics and Automation Letters*, 5(1):8–15, 2020.

[ZHZ$^+$18] Zhiyuan Zhao, Shuai He, Yaping Zhao, Ce Xu, Qingwen Wu, and Zhenbang Xu. Workspace analysis for a 9-dof hyper-redundant manipulator based on an improved monte carlo method and voxel algorithm. In *Proceedings of International Conference on Mechatronics and Automation*, pages 637–642, Changchun, China, August 05–08 2018. IEEE.

[ZKA12] SHH Zargarbashi, Waseem Khan, and Jorge Angeles. Posture optimization in robot-assisted machining operations. *Mechanism and Machine Theory*, 51:74–86, 2012.

# Journal and Conference Publications

- **Title:** Design and Kinematic Analysis of a Novel 2-DoF Closed-Loop Mechanism for the Actuation of Machining Robots
- **Conference:** ASME/IDETC-CIE 2021
- **Date:** August 17 – 20, 2021
- **Abstract:** The essential characteristics of machining robots are their stiffness and their accuracy. For machining tasks, serial robots have many advantages, like a larger workspace, but they lack the necessary stiffness to accomplish high machining effort tasks. One way to increase the stiffness of serial manipulators is to make their joints using closed-loop or parallel mechanisms instead of using the classical prismatic and revolute joints. This increases the accuracy of a manipulator without reducing its workspace. This paper introduces an innovative two degrees of freedom closed-loop mechanism and shows how this mechanism can be used to build high stiffness and large workspace serial robots. The design of this mechanism is described through its geometric and kinematic models. Then, the kinematic performance of the mechanism is analyzed, and a serial arrangement of several such mechanisms is proposed to obtain a potential design of a machining robot.
- **Reference:** Angelica Ginnante, François Leborne, Stéphane Caro, Enrico Simetti, and Giuseppe Casalino. Design and kinematic analysis of a novel 2-dof closed-loop mechanism for the actuation of machining robots. In *Proceedings of International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, volume 85444, Online, Virtual, August 17–19 2021. American Society of Mechanical.

- **Title:** Kinetostatic Optimization for Kinematic Redundancy Planning of Nimbl'Bot Robot
- **Journal:** Journal of Mechanism and Robotics (ASME)
- **Date:** March 27, 2023
- **Abstract:** In manufacturing industry, Computer Numerical Control (CNC) machines are often preferred over Industrial Serial Robots (ISR) for machining tasks. Indeed, CNC machines offer high positioning accuracy, which leads to slight dimensional deviation on the final product. However, these machines have a restricted workspace generating limitations in the machining work. Conversely, ISR are typically characterized by a larger workspace. ISR have already shown satisfactory performance in tasks like polishing, grinding and deburring. This paper proposes a kinematic redundant robot composed of a novel two degrees-of-freedom mechanism with a closed kinematic chain. After describing a task priority inverse kinematic control framework used for joint trajectory planning exploiting the robot kinematic redundancy, the paper analyses the kinetostatic performance of this robot depending on the considered control tasks. Moreover, two kinetostatic tasks are introduced and employed to improve the robot performance. Simulation results show how the robot better performs when the optimization tasks are active.
- **Reference:** Angelica Ginnante, Stéphane Caro, Enrico Simetti, and François Leborne. Kinetostatic optimization for kinematic redundancy planning of nimbl'bot robot. *Journal of Mechanisms and Robotics*, 16(3), 2023.

- **Title:** Task Priority Based Design Optimization of a Kinematic Redundant Robot
- **Journal:** Mechanism and Machine Theory
- **Date:** May 9, 2023
- **Abstract:** This paper presents and defines a new design optimization method for kinematic redundant robot manipulators based on their applications. Kinematic redundant manipulators can reach a pose with an infinite number of postures. So, identifying the best robot design and configuration for a set of desired tasks is a highly complex non-linear problem. This approach employs a task priority control algorithm to perform a task oriented robot design optimization. The design parameters are replaced by controllable prismatic or revolute virtual joints and controlled by the algorithm to accomplish the desired tasks. Therefore, this new method finds an optimal robot design for a set of tasks taking advantage of the robot kinematic redundancy. This method is evaluated on a highly kinematic redundant manipulator, which tracks a set of paths with its end-effector while maintaining good kinetostatic performance.
- **Reference:** Angelica Ginnante, Enrico Simetti, Stéphane Caro, and François Leborne. Task priority based design optimization of a kinematic redundant robot. *Mechanism and Machine Theory*, 187:105374, 2023.

- **Title:** Workspace Determination of Kinematic Redundant Manipulators Using a Ray-Based Method
- **Conference:** ASME/IDETC-CIE 2023
- **Date:** August 20 – 23, 2023
- **Abstract:** Determining the workspace of a robotic manipulator is extremely significant for knowing its abilities and planning the robot application. There exist several techniques for the robot workspace determination. However, these methods usually are affected by computational redundancy, like in the case of Monte Carlo based methods, or their implementation is difficult. Moreover, the workspace analysis of kinematic redundant manipulators is even more complex. This paper introduces a ray-based workspace determination algorithm, easy to implement and not affected by computational redundancy. The proposed method can be applied to any type of serial robot, but it is tested only on spatial kinematic redundant robots. The results show how the approach can clearly determine the boundary of the robot workspace in a short period of time. Finally the time and quality performance of the ray-based method results are compared to the Monte Carlo one demonstrating the improvement of the proposed method.
- **Reference:** Angelica Ginnante, Stéphane Caro, Enrico Simetti, and François Leborne. Workspace determination of kinematic redundant manipulators using a ray-based method. In *Proceedings of International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.* Conference, Boston, Massachusetts, August 20–23 2023. American Society of Mechanical Engineers.

**Titre:** Conception, analyse et contrôle cinématique de bras robotiques en série hautement redondants

**Mots clés:** redondance cinématique, priorité des tâches, performance cinétostatique, optimisation de la conception, analyse de l'espace de travail

**Résumé:** L'utilisation de manipulateurs robotiques dans l'industrie s'est développée au cours des dernières décennies afin d'améliorer et d'accélérer les processus industriels. Les manipulateurs industriels ont commencé à être étudiés pour les tâches d'usinage car ils peuvent couvrir de plus grands espaces de travail, ce qui augmente la gamme d'opérations réalisables et améliore la flexibilité. La société Nimbl'Bot a mis au point un nouveau mécanisme, ou module, pour construire des robots modulaires en série plus rigides et plus flexibles pour les applications d'usinage. Ce manipulateur est un robot redondant cinématique à 21 degrés de liberté. Cette thèse analyse en profondeur les caractéristiques du robot Nimbl'Bot et est divisée en trois sujets principaux. Le premier sujet concerne l'utilisation d'un algorithme de résolution de redondance cinématique prioritaire pour la trajectoire de suivi du robot Nimbl'Bot tout en optimisant ses performances cinétostatiques. Le deuxième sujet est l'optimisation de la conception d'un robot à redondance cinématique en fonction d'une application souhaitée et de ses performances cinétostatiques. Pour le troisième sujet, un nouvel algorithme de détermination de l'espace de travail est proposé pour les manipulateurs redondants cinématiques. Plusieurs tests de simulation sont proposés et testés sur quelques conceptions de robots Nimbl'Bot pour chaque sujet.

**Title:** Design, analysis and kinematic control of highly redundant serial robotic arms

**Keywords:** kinematic redundancy, task priority, kinetostatic performance, design optimization, workspace analysis

**Abstract:** The use of robotic manipulators in industry has grown in the last decades to improve and speed up industrial processes. Industrial manipulators started to be investigated for machining tasks since they can cover larger workspaces, increasing the range of achievable operations and improving flexibility. The company Nimbl'Bot developed a new mechanism, or module, to build stiffer flexible serial modular robots for machining applications. This manipulator is a kinematic redundant robot with 21 degrees of freedom. This thesis thoroughly analysis the Nimbl'Bot robot features and is divided into three main topics. The first topic regards using a task priority kinematic redundancy resolution algorithm for the Nimbl'Bot robot tracking trajectory while optimizing its kinetostatic performances. The second topic is the kinematic redundant robot design optimization with respect to a desired application and its kinetostatic performance. For the third topic, a new workspace determination algorithm is proposed for kinematic redundant manipulators. Several simulation tests are proposed and tested on some Nimbl'Bot robot designs for each subjects.

**Titolo:** Progettazione, analisi e controllo cinematico di bracci robotici seriali altamente ridondanti

**Parole chiave:** ridondanza cinematica, priorità dei task, prestazioni cinetostatiche, ottimizzazione del design, analisi dello spazio di lavoro

**Riassunto:** L'uso di manipolatori robotici nell'industria è cresciuto negli ultimi decenni per migliorare e velocizzare i processi industriali. I manipolatori industriali hanno iniziato a essere studiati per le attività di lavorazione, poiché possono coprire spazi di lavoro più ampi, aumentando la gamma di operazioni realizzabili e migliorando la flessibilità. L'azienda Nimbl'Bot ha sviluppato un nuovo meccanismo, o modulo, per costruire robot modulari seriali più rigidi e flessibili per applicazioni di lavorazione. Questo manipolatore è un robot cinematico ridondante con 21 gradi di libertà. Questa tesi analizza a fondo le caratteristiche del robot Nimbl'Bot ed è suddivisa in tre argomenti principali. Il primo argomento riguarda l'utilizzo di un algoritmo di risoluzione della ridondanza cinematica a priorità di compito per la traiettoria di inseguimento del robot Nimbl'Bot, ottimizzando le sue prestazioni cinetostatiche. Il secondo argomento è l'ottimizzazione del design del robot con ridondanza cinematica rispetto a un'applicazione desiderata e alle sue prestazioni cinetostatiche. Per il terzo argomento, viene proposto un nuovo algoritmo di determinazione dello spazio di lavoro per manipolatori cinematici ridondanti. Per ogni argomento vengono proposti e testati diversi esperimenti in simulazione con alcuni design di robot Nimbl'Bot.