Dimensional Synthesis of a Robotic Arm for Mobile Manipulator Using an Interactive Geometry Software

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Abstract. This paper aims to demonstrate a systematic procedure for the structural selection and dimensional synthesis of the arm to be integrated into a mobile manipulator. The manipulator will be utilized for Bots2ReC H2020 project which aims at developing an autonomous robotic solution for removing asbestos contamination from real world-rehabilitation sites. The synthesis procedure is initiated by identifying requirements and constraints on the mobile manipulator. The Interactive Geometric Software (IGS) is used to carry out the preliminary synthesis. The synthesis procedure highlights the utility of IGS in developing the conceptual and dimensional design of the arm and assesses its performance to satisfy given requirements and constraints. Redundancy is used to meet the desired requirements while satisfying the constraints.

Key words: structural selection, dimensional synthesis, skeleton modeling, interactive geometric software, redundant architecture, mobile manipulator

1 Introduction

Mobile manipulators have gained an increasing popularity in automated industrial environments with applications ranging from assembly of large scale parts, surface processing, material handling, flexible manufacturing, etc [2]. Mobile base enables movement of the robotic arm in the work environment which then performs the required task. Thus, while synthesizing robotic arms for mobile manipulators; mobility of the base needs to be considered in order to determine the exact positioning of the robotic arm for performing a given task.

Synthesis methods and optimization techniques [6, 10, 13] have been proposed for dimensional synthesis of serial and parallel manipulators. The design process generally starts with conceptual design that permits fast exploration of many solutions and preliminarily assessment of their functionality. Geometry sketchers and CAD tools are well known for performing such design activity. In [11], two geometry sketchers and two CAD systems were compared. Interactive Geometric Software (IGS) were found to be particularly efficient for fast, preliminary dimensional synthesis of linkages. IGS are mostly used for educational purposes [4, 8]. In [9, 12] common IGS used into different fields regarding synthesis were compared. GeoGebra [7] was found better with regard to its interface and use for design methodology. In [1] a new method for determination and optimization of the workspace of parallel manipulators is presented. The proposed method is based on a geometrical approach, and offers the possibility to generate automatically the workspace in a CAD environment. By taking motivation from these works, this paper presents a technique for the preliminary synthesis of arm architecture for a mobile manipulator that will be used for the H2020-Bots2ReC project [3]. A broad objective of this project is "introducing, testing and validating an operational process for the automated removal of asbestos contamination at a real world rehabilitation site using a robotic system".

The emphasis while designing the entire operational process will be to optimize the performance of the system by improving asbestos *cleaning productivity* while ensuring a safe and stable operation. Cleaning productivity can be maximized using one or several optimization functions such as – amount of asbestos cleaned per unit time, surface area cleaned per unit time or total time required to clean a standard rehabilitation site. Productivity is impacted by several factors such as: *maximum achievable displacement speed*, *trajectory planning of the robotic arm*, *motion planning of the moving platform*, *task allocation and planning*, etc.

In section 2, requirements and constraints of the cleaning operation which serve as an input to arm synthesis are identified. Section 3 presents the dimensional synthesis of the arm using the IGS Geogebra. In section 4, workspace of the synthesized architecture is characterized. Section 5 concludes the dimensional synthesis procedure presented in this paper.

2 Requirements and Constraints

Identifying requirements is the first necessary step while formalizing a design problem. The challenge in satisfying these requirements is overcoming constraints imposed by the interaction of the system with real world. This section identifies all such requirements and constraints that will be taken into account for the synthesis of the arm architecture and dimensions.

Performing asbestos removal while the mobile base is in motion is a critical task as the control of the grinding becomes difficult. Hence, it was decided to first fix the mobile base in a given pose with stabilizers and then to operate the arm from this pose. In such scenario, as the stabilization of the mobile platform takes some time, the robotic arm must be able to clean as much area as possible for the given pose of the mobile platform. To achieve this, the workspace of the arm should be as large as possible. Thus, productivity improvement is associated with the dimensional synthesis of the arm architecture.

Table 1. Requirements and constraints on the mobile manipulator expressed as Design Rules

Requirements and Constraints	*Design Rule*
The end-effector must reach Floor, wall, ceiling **(3m high)**, skirting, etc and still be capable to work	**DR_Env** Types of surfaces to be cleaned; The mobile manipulator has a minimal reach of 3 m from the ground and is free of singular configurations, even on the workspace boundary
Surfaces to be cleaned can be horizontal, vertical, inclined, flat or curved, etc.	**DR_Surf** Shape of surfaces to be cleaned; Required DoFs are: 3 translations and 2 rotations (disc tool) or 3 rotations (cylindrical tool)
Safe and stable cleaning operation of the mobile manipulator is required	**DR_Stab** Static stability; Lateral and Longitudinal stability margins must be satisfied throughout cleaning operation
The mobile manipulator should be transported to cleaning sites through elevators	**1. DR_Mass** Mass of the mobile manipulator; The overall mass of the mobile manipulator must be lower than 300 kg **2. DR_Short arm;** Arm should be as short as possible
The mobile manipulator must pass through doors of dimensions (80x200 cm) and fit in an elevator 200 cm high	**DR_Dim** Overall dimensions; The mobile manipulator must provide a pose fitting in a parallelepiped envelope of (80x60x190cm)
The mobile manipulator should be capable to clean corridors as narrow as 70 cm	**DR_Narrow_Corridors** The projected workspace on the walls of the corridors should be as wide a s possible
Collision of links of the arm with the mobile platform or environment surfaces must be avoided	**DR_Non_Collision** Collision avoidance; Link lengths must be optimized for avoiding collisions

The choice of suitable arm kinematics for the arm must be made considering DR_Surf and DR_Env. Two rotational *DoFs* of the *end-effector* can be assumed in the wrist for orienting the tool while the three translational *DoFs* for reaching desired position. For dimensional synthesis, wrist can be ignored which leaves us with kinematics of 3 translational *DoFs*. Such kinematics can be realized as RPR or RRR serial chain. The design team chose to focus on the first RRR solution and other kinematics will be considered if the first one does not bring a solution.

3 Dimensional synthesis of the arm

For the synthesis, a skeleton modeling approach is used through which, links are represented by lines and joints are reduced to points and/or motion axis [5,11]. One solution to satisfy simultaneously contradictory design rules {DR_Env}, that requires a sufficient reach of the arm and {DR_Dim, DR_Non_Collision, DR_Short_ARM}, that tend to limit link lengths, is the following design rule: DR_Mid_Dist : locating the arm base at mid-distance between ground and 3 m high ceiling and provide arm ream superior to 1.5 m.

The analysis can be restricted to 2D by fixing the base revolute joint which reduces kinematics to RR. Moreover, DR_Narrow_Corridor is also critical and likely to affect the link lengths. Thus, considering the most critical case, dimensional synthesis is performed for cleaning inside narrow corridors. To summarize the design problem, the important design parameters are identified as: ***reachability***, ***singularity avoidance, collision avoidance*** and ***continuous trajectory.*** For a continuous horizontal motion along X, the most critical pose is when the arm is in the plane BYZ.

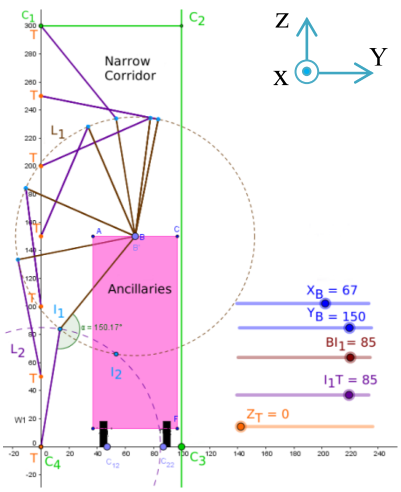

Fig. 1 Arm-wall and arm - platform collisions

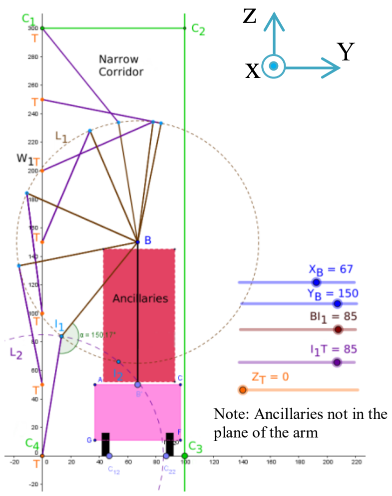

Fig. 2 Arm-wall collisions

In Fig. 1, a narrow corridor is represented in a Geogebra model in cross-section by the rectangle $C_1C_2C_3C_4$. The parametrizing capacity of Geogebra is used to explore the design space and move the end-effector vertically along the wall. Point B represents the base of the arm and is adjusted at 150 cm height with the Y_B slider, according to DR_Mid_Dist. By fixing the base B, circle (L_1) that characterizes the first link is (parameterized by slider BI_1). For constructing the second link, the end-effector point T is first fixed at a position on the wall represented by the Y-axis. Another circle (L_2) that characterizes the length of second link is parameterized by slider I_1T. Two intersection points I_1 and I_2 are obtained that are the two possible elbow points. Point I_1 (elbow-up) configuration is chosen.

Fig.1 shows the issue of collision of the elbow joint with the wall as well as Link 1 with the mobile platform while performing vertical trajectory. Fig.2 proposes an alternate design of the mobile platform to avoid arm-platform collision. In this design, the red box indicating ancillaries is mounted behind the working plane of the arm and hence does not interfere within the workspace. However, arm-wall collisions can't be avoided. Thus, DR_Non_collision is not satisfied. one solution to satisfy the design rule DR_non_collision is to infer the new following design rule: "DR_Link_1: for avoiding collision, the link length of the first link must not exceed the distance between the base position, B and the front wall. Thus, the input radius for circle L_1 (which controls the link length L_1) is given as the X-coordinate of the point B. Hence any change in the position of B automatically modifies link 1. Similarly, to avoid the collision of elbow with wall C_2C_3, a design rule for second link can be obtained as: "DR_Link2: link 2 should be less that the width of the corridor".

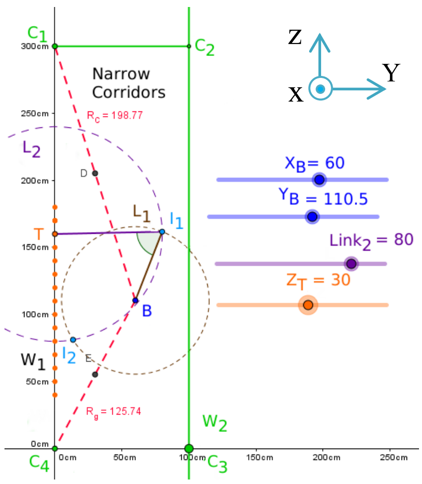

Fig. 3 Collision avoidance with wall C_1C_4

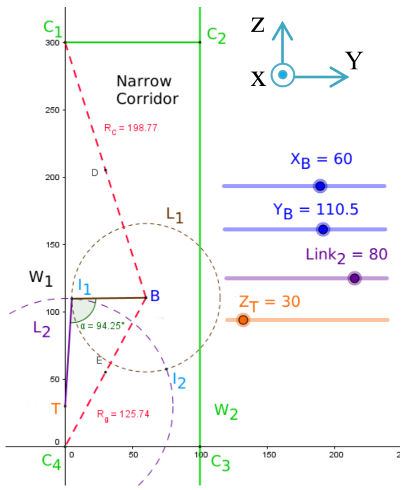

Fig. 4 Collision avoidance with wall C_2C_3

However, for link lengths obtained by following these two rules, it is impossible to reach both ceiling and ground points by keeping the base position fixed. Hence, need of a vertical shift in the base point B is identified. This adds another joint i.e, a prismatic joint in the base of the robot, hence making the architecture redundant. Thus, redundancy is used to avoid the issue of collision in corridors. Figures 3 and 4 show that the DR_Env is satisfied. Maximum and minimum vertical displacement of the point B is 180 cm and 100 cm respectively.

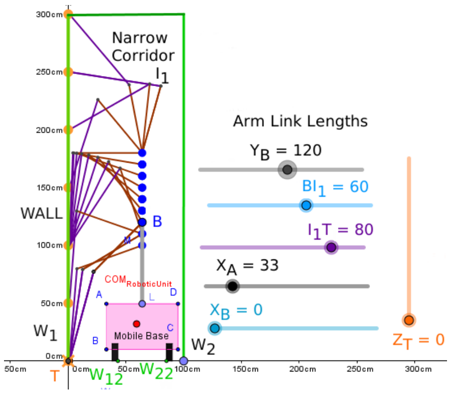

Fig. 5 Continuous wall Vertical Trajectory

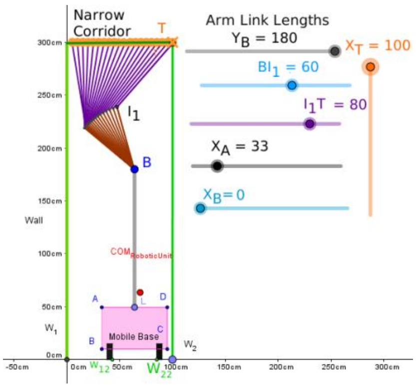

Fig. 6 Continuous ceiling trajectories

4 Estimation of 3-D workspace

The analysis carried out in section 3 was limited to 2D where only one working plane of the workspace was considered. In this section, a 3D workspace is evaluated using Geogebra 3-D module. The interest of plotting the workspace is to evaluate the area covered by it on the cleaning walls.

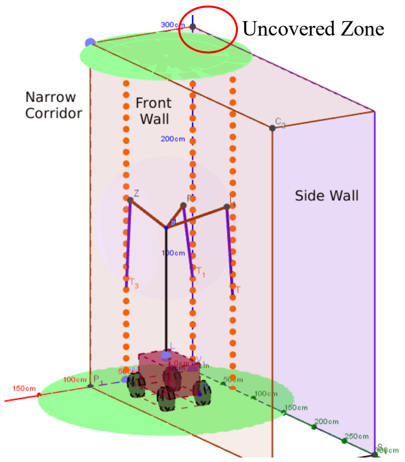

Fig. 7 Intersection of the workspace with ground and ceiling

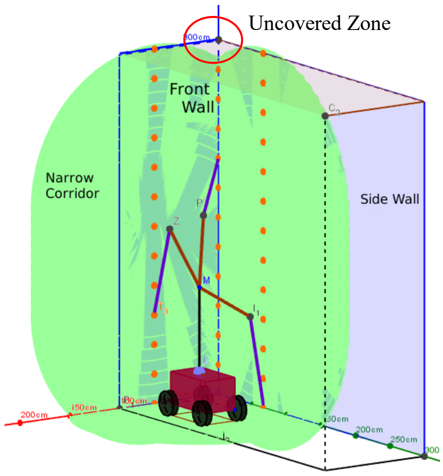

Fig. 8 Intersection of the workspace with side and front wall

In Fig.7, intersection of the 3D workspace with plane ceiling and ground is presented. The size of the ground and ceiling workspace directly depend on the slider stroke positioning; the ceiling workspace can be enlarged and the ground workspace can be reduced if the slider stroke is positioned higher. A wider ground-workspace for covering the ground all around the mobile base can be seen In Fig. 7. Similarly in Fig. 8, intersections of the workspace with the front and the side wall are presented. Zones not covered inside the workspace, mostly in the corners are highlighted with red circles showing that the workspace will not be completely reached by the arm with the current configuration of the mobile platform. To access such areas, one needs to relocate the platform. However, the designed arm is seen to cover most of the cleaning area without collisions.

5 Conclusions

In this paper, an anthropomorphic arm structure is synthesized using inference of design rules and 2D parametrized models in an Interactive Geometric Software (IGS). The synthesis method is based on a loop of series of two stages:

1. Inference of design rules that determine geometrical properties represented in simplified models.
2. The geometric model is simulated. If the design rule is seen to be violated (e.g. collision, singularity...), a better restrictive design rule is inferred and the loop continues.

The kinematics designed has a sufficient workspace and can perform a 3 m high continuous trajectory while avoiding singularities. The width of the workspace is constrained in the narrow corridor scenario: the most critical pose is when the arm is located on the lateral plane (BYZ) passing through the arm base point. As the RR arm architecture generates too many collisions a redundant PRR kinematics was proposed. Adding redundancy to the originally considered architecture was proved to generate a better compact design avoiding collisions and allowing singularity-free continuous vertical trajectories.

This work proved the interest of combining design rule inference and skeleton modelling using IGS in order to perform dimensional synthesis of an arm for mobile manipulator. The design rules are helpful for converting requirements into geometrical constraints. The IGS is powerful software for expressing design constraints in the Cartesian space and exploring the design space through parametrization. The IGS permitted to extract new design rules that allow local geometrical optimization of the mechanism in the design space.

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