VOLUME 16, N° 1 2022
Journal of Automation, Mobile Robotics and Intelligent Systems

Selection of Manipulator Configuration for a Portable Robot for Special Tasks

Submitted: 22nd September 2021; accepted 8th February 2022

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DOI: 10.14313/JAMRIS/1-2022/3

Abstract:
This paper presents a method of selection of configuration for manipulators of portable robots for special purposes. An analysis of tasks and related requirements for the functionality of the manipulator was presented on the example of the portable PIAP Patrol robot. From the set of robot tasks, the tasks that had the greatest impact on the manipulator parameters were selected. Both kinematic and static criteria were used as the basis for adopting the objective function. With the use of multi-criteria optimization tools, the manipulator configuration parameters were selected. Selected working capacities were maximized while ensuring that the imposed requirements for mass and kinematic limitations were met. The results of simulation tests were presented, and the scope of further work has been outlined.

Keywords: *Field robotics, EOD robots, manipulators*

1. Introduction

Among mobile robots dedicated to special applications, one can distinguish those that are man-packable, weighing up to 15 kg, and 2-man portable robots weighing up to 75 kg. [1] [2]. The users of portable robots indicate the mass and load to mass ratio as important features of the robot [3][4]. Striving to reduce the mass of the robot's components must not adversely affect the operating capabilities and parameters. This article presents an analysis of the literature on the selection of manipulator parameters and presents a new approach to the selection of the robot manipulator configuration, in which the main criterion was the analysis of tasks performed by robots for special tasks. On the example of the portable PIAP Patrol robot, the analysis of tasks and related requirements for the functionality of the manipulator has been presented.

In the process of selecting the manipulator parameters, a model was used consisting of joints represented by point masses and connectors with a specific mass of an arm section of a unit length. The parameters of the joints were selected, indicating the distances between the axes – the lengths of the links and the sizes of the executive modules in the joints.

From the set of robot tasks, the characteristic tasks that have the greatest impact on the manipulator parameters were selected. The selection was made using both kinematic and static criteria.

This was the basis for adopting three objective functions: maximization of horizontal reach, maximization of lifting capacity at maximum reach, and maximization of load capacity at a certain minimum distance from the body of the mobile platform.

With the use of multi-criteria optimization tools, we carried out the selection of the manipulator configuration parameters, which leads to the maximization of selected working capacities while ensuring that the imposed requirements and mass and kinematic limitations are met. The results of simulation tests were presented and the scope of further work was outlined.

2. Related Works

The process of selecting parameters for manipulators has been presented in many papers. Z. Du, Y. Xiao, and W. Dong carried out a multi-criteria optimization of the geometric parameters of the manipulator and gear parameters to minimize the mass-to-load ratio and to maximize the natural frequency of the structure [5]. The authors used the NSGA-II algorithm and checked the results in the ADAMS system. Thanks to optimization, they achieved a 10% mass reduction. H. Yin, S. Huang, M. He, and J. Li proposed a method of designing a manipulator in which the optimization of parameters for design and the selection of manipulator drives was performed [6]. The manipulator mass was minimized while maintaining the constraints resulting from the assumed robot dynamics. Parametric optimization was performed in the Ansys program and a manipulator model simulated in the ADAMS system was used for the selection of drives.

In another paper, C. Lanni, S. F. P. Saramago, and M. Ceccarelli formulated the task of manipulator design as a problem of optimization, in which the objective functions are minimization of the size of the manipulator and maximization of workspace volume [7]. The numerical solution of the optimization problem was solved by using two different numerical techniques: sequential quadratic programming and simulated annealing.

H. Lim, S. Hwang, K. Shin, C. Han and presented the procedure and the results of the multi-objective optimization for designing a seven-degree-of-freedom (7DOF) robot manipulator with higher global performance [8]. Global performance was defined by the global conditioning index and the structural length index, which represents the ratio of the total link length of the robot manipulator to the volume of the reachable workspaces. Analysis of variance (ANOVA) was completed, both to analyze the effect of the link parameters on the performance of the robot manipulator, and to find which link parameter affects the performance of the robot manipulator. The results of the optimization of the prototype robot manipulator were presented.

Wang X. et al. optimized the serial manipulator by integrating topology optimization and parametric system optimization [9]. Scientists at first constructed the stiffness model of the manipulator, then determined typical load configurations and loads. On the part level, they performed topology optimization. On the system level, they performed parametric optimization, which was used to determine the mass division into different components.

Xu Q. et al optimized the link lengths of an anthropomorphic manipulator [10]. The authors defined a global comprehensive performance index considering manipulability, the Jacobian matrix condition number, and end stiffness of the manipulator. The index was used to measure performance during optimization.

Lim et al. optimized 7 DOF manipulators' parameters using Genetic Algorithm and Modified Dynamic Conditioning Index as an objective function [11].

The conducted analysis of the literature shows that although the topic of selecting the parameters of manipulators was undertaken by many authors, the problem of selecting the configuration of manipulators in the context of mobile robotics for special tasks was not discussed in the available literature.

3. Robots for Special Tasks

The specificity of mobile robots for special applications such as intelligence, surveillance, and reconnaissance; combat support; mine clearance; detection and neutralization of explosives; counteracting CBRN threats; transport; search and rescue; and firefighting requires an individual approach to their design, taking into consideration desired mobility and working capacity. According to technical report. [4], the robots carrying out the above-mentioned tasks should be capable of:

- detection of thin lines, antennas, cables, and wires, metals masked with ground, and explosives;
- observation of objects, both low-lying (e.g., under a car) as well as objects located high above the robot;
- picking up or removing objects with a manipulator;
- revealing objects in the ground;
- excavating items;
- checking passenger cars and trucks (chassis, interior, trunk);
- checking culverts and bridges;
- neutralization of IEDs by alternative methods.

Each of these tasks is associated with specific requirements for both the platform and its equipment. The manipulator is the basic equipment of the robot, which is often jointed with the platform. In terms of the manipulator's working abilities, the following tasks should be considered:

- picking up and carrying objects, opening the door with a gripper;
- exposing, digging, and burying in the ground with the help of additional equipment;
- moving and dragging objects on the ground using a gripper or an arm;
- cutting wires, wires, rods, punching tires, breaking windows with the help of additional equipment mounted in the gripper;
- carrying out neutralization with a shotgun or pyrotechnic disruptor mounted on the manipulator (various mounting configurations);
- X-raying objects with the use of additional equipment mounted in the gripper;
- freezing objects with liquid nitrogen, using a lance fixed in the gripper;
- sampling and measurements with CBRN sensors mounted on the gripper or arm;
- placing charges with a gripper;
- conducting reconnaissance and observation of sensors installed on the manipulator.

The robots work in an unstructured environment, with limited situational awareness of the operators. As a result, the structure of the manipulator must also be resistant to such events as hitting obstacles, lifting the platform to the working position in the case of a rollover, or balancing and supporting the mobile platform while overcoming obstacles.

Backpack-class robots must be light enough for soldiers to carry them for extended periods, or, in the case of a portable class, to be carried by 2 people. This results in the requirements for the mass and dimensions of the robot in the transport position.

The basis for the reduction of the structure mass is the identification of loads to which the structure will be subject, as well as the definition of the critical load states that will be taken into account during the calculations. During operation, the manipulator of a mobile robot for special tasks is subject to complex loads:

- quasi-static loads resulting from lifting and shifting objects with a gripper or a working tool, such as lifting the maximum load to be lifted with the grapple from the ground, lifting the maximum load from ground level for the maximum reach of the arm, moving objects along the ground with the grapple by rotating the platform in place, loading of the manipulator through the thrust on, or pulling a stationary object with the robot's drive system;
- loads from digging and burying in the ground;
- dynamic loads resulting from the movement of the mobile platform over obstacles, curbs, stairs, etc. It can also be a drop of a robot with a manipulator from a given height;
- vibrations resulting from the tread or segments of the track system of the mobile platform;
- dynamic loads from pyrotechnic ejectors or shotguns mounted on the manipulator's arm;
- dynamic loads resulting from robot operator errors.

Some loads can be determined analytically, and some require measurements or simulations. Recoil tests during shots with a rifle or pyrotechnic disruptor have been carried out by many scientists and the results have been presented in several papers [12-14]. The results of these experiments will be used at a later stage to model the stroke while firing a shotgun attached to the robot manipulator arm.

It is necessary to define what combinations of the above-mentioned loads are possible, and, on this basis, to select key load states. It should also be considered that preparing the structure for some hypothetically possible loads may be difficult and costly. An example of such a load may be a collision with the full speed of movement of the platform, a fully deployed side-facing robot manipulator, e.g., with a tree. Securing the structure for such an eventuality may be expensive and complicated. It may be necessary to assume that such a threat would be eliminated by appropriate training and, for example, a function of reduction of the robot's speed in the configuration with an unfolded arm, implemented in software. Risk analysis would allow for the development of a structure tailored to the requirements which would not be oversized.

4. Selection of the Configuration of the Manipulator

The aim of the work carried out at Łukasiewicz PIAP was to develop a method for selecting the parameters of the manipulator structure with the assumed maximum lifting capacity and range, ensuring that the mass limit and other requirements and limitations resulting from the tasks of mobile robots would be met.

This task has been decomposed into the following subtasks:

1. Selection of parameters of drive modules and link lengths.
   In the sub-task, the parameters of the drive modules and the arm lengths will be selected to obtain the most advantageous combination of parameters, considering the expected requirements.
2. Development of a family of reduced-mass drive modules
   The structure of drive modules with a minimum mass for the loads resulting from the tasks should be developed for the components in the subtask. One of the possible methods is topological optimization.
3. Selection of actuator components with the best load-to-mass ratio.
   This subtask should analyze the parameters of the components that can be used. The key is the selection of the last gear stage in the manipulator drive. The most commonly used gears with perpendicular axes are worm gears (e.g., Med-Eng, ECA, Łukasiewicz-PIAP) or spiroid gears (Teledyne Flir) with a high ratio. The design of the drive modules and the entire manipulator will depend on the type of gear.

At each stage of the above-mentioned subtasks, the requirements and limitations typical for robots for special tasks are important. They affect working loads, working space, the need for electromagnetic shielding, environmental sealing, etc. As part of the article, the authors will focus on the selection of the manipulator parameters listed as the first subtask.

5. Model of the Manipulator

The PIAP Patrol robot can be used as an example of a portable robot. This robot is equipped with a manipulator (Fig. 1) with five rotational degrees of freedom. The first axis is vertically oriented, the second, third and fourth are parallel and horizontally directed, the fifth axis is responsible for the rotation of the gripper about its axis. The structure of the manipulator's arms includes joints with actuator mechanisms and links, the length of which can be easily modified.

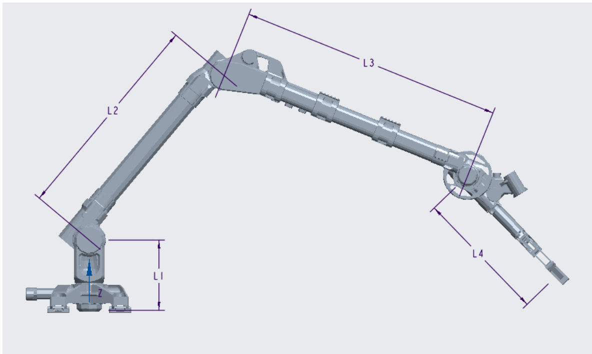


Fig. 1. View of PIAP Patrol manipulator

In the process of selecting the parameters of the manipulator, a model with a structure similar to that of the PIAP Patrol robot was used, consisting of joints represented by point masses and connectors with a specific mass of an arm section of a unit length (Fig. 2).

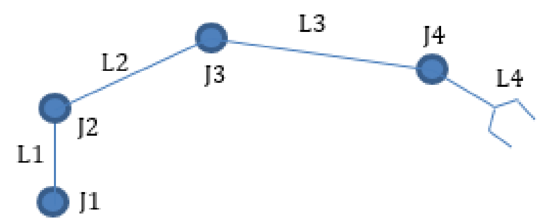


Fig. 2. Model of the manipulator

The parameters of the joints were selected, indicating the distances between the axes – the links lengths and the sizes of the actuator modules in the joints. For such a task, the manipulator configuration is described by the vector:

$$Man\_config = [J1, J2, J3, J4, L1, L2, L3, L4]$$

where:

$J1$, $J2$, $J3$, $J4$ – ID numbers of the actuator modules used in the manipulator's joints

$L1$, $L2$, $L3$, $L4$ – distances between the joints

Actuator module sizes $J1$, $J2$, $J3$, and $J4$ are selected from the family of sets. This approach is justified, because when designing a transmission, it is often not possible to choose the components freely, but the constructor must instead select components from the family of parts available from manufacturers. Such a limitation often results from the necessity to unify subassemblies and limit the assortment of various ordered and stored parts.

In the *Man_config* vector, the joint size is represented by the ID number of the selected actuator module for each joint. The joint is defined as a vector

Joint = [*J_ID*,*J_T*,*J_m*]

where:

J_ID – ID number of actuator module,

J_T – designated torque of actuator,

J_m – a mass of the actuator module

For the construction of the gearbox, the use of commercial components sets was assumed, and 13 sets were selected with parameters listed in Table 1.

Table 1. Family of actuator modules

J_ID	J_T Joint torque [Nm]	J_m Joint mass [kg]
1	26	0,90
2	29	0,93
3	35	0,99
4	38	1,02
5	79	1,42
6	96	1,58
7	153	2,14
8	173	2,33
9	230	2,88
10	306	3,62
11	398	4,51
12	610	6,56
13	722	7,65

The maximum torque values presented in Table 1 result from the torque limitation with the overload clutch. The mass of the joint presented in Table 1 was estimated based on the analysis of the existing examples of joints of the manipulators of mobile robots. Apart from the transmission components such as the worm and the worm wheel, the mass of the joints includes the body, shafts, bearings, seals, overload friction clutch, clutch, the motor with planetary gear, position sensors, and controllers. Figure 3 shows the points from which the relationship was determined, which approximates the mass of the joints depending on the maximum moment. The linear form of the regression function has been adopted.

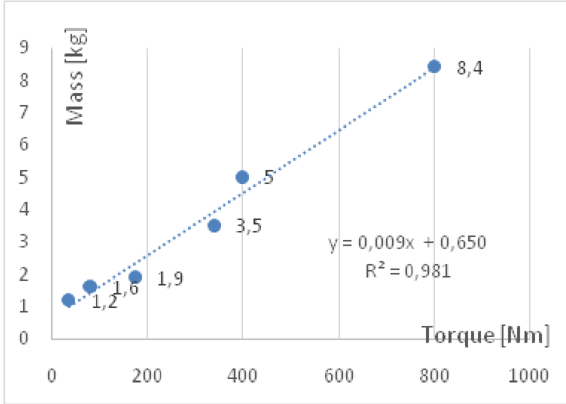


Fig. 3. The dependence of the joint mass on the transmitted torque

6. Criteria for Evaluating the Manipulator

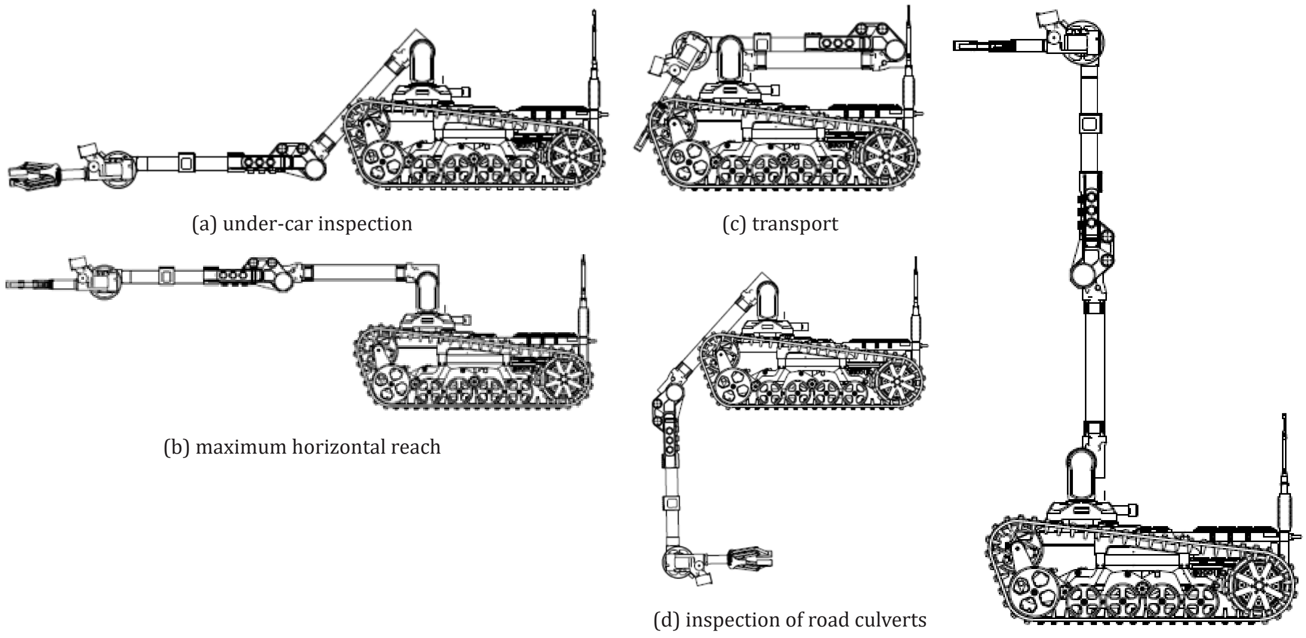
From this set of tasks, the characteristic tasks that have the greatest impact on the parameters of the manipulator were selected. The criteria have been divided into kinematic and static. Kinematic criteria are responsible for ensuring the possibility of adopting the appropriate configuration for the planned tasks and they mainly affect the lengths of the links. Static criteria are responsible for ensuring that loads can be picked up in selected positions.

The following kinematic criteria were considered:

a) Maximizing the reach when reaching under the car (Fig. 4a).
b) Maximum horizontal reach (Fig. 4b).
c) Minimizing the dimensions of the robot in its folded position (Fig. 4c).
d) Maximize reach when reaching down below the ground level (Fig. 4d).
e) Maximum vertical reach for picking up a load (Fig. 4e).

When in tight spaces, it is advantageous when the gripper is short, so the length was fixed and excluded from the optimization process. The length was assumed based on the analysis of the existing structure. It was assumed that due to the necessity to maintain minimum dimensions during transport (Figure 4c), the height of the first manipulator member should be the minimum possible and was determined by the analysis of the existing structure. This ensures minimization of the folded robot's height.

When working in tight spaces, it is advantageous when the gripper is short, so the length was fixed and excluded from the optimization process. The length was assumed based on the analysis of the existing structure. It was assumed that due to the necessity



(a) under-car inspection (c) transport

(b) maximum horizontal reach

(d) inspection of road culverts

(e) maximum vertical reach

Fig. 4. Characteristic configurations of the manipulator

to maintain minimum dimensions during transport (Figure 4c), the first manipulator member should be the minimum height possible, which was determined by the analysis of the existing structure. This ensures minimization of the height of the folded robot.

As the waist and gripper lengths have been fixed, the arm and shoulder length of the manipulator have been further optimized.

This allowed us to reduce the criteria a) and e). Maximizations of the horizontal reach and maximization of vertical reach requirements coincided, because both meant that the longer the sum of L2 and L3 is, the better. These criteria were reduced to one criterion: the maximization of the horizontal range.

To be able to perform a visual inspection of the car chassis (requirement a), the arm-length condition has been added, to provide the possibility of lowering the shoulder joint above the ground. Case d) of the criteria was no longer considered because it coincided with cases b) and a).

The possibility of rotating the axis waist (the first–vertical axis) of the manipulator and the fifth axis responsible for the rotation of the gripper around its axis was not taken into account. In this case, the task of selecting parameters could be treated as two-dimensional.

Static criteria following objective functions were considered:

- maximization of lifting capacity at maximum reach;
- maximization of the load capacity when picking up the load at a certain minimum distance from the body of the mobile platform (Fig. 5).

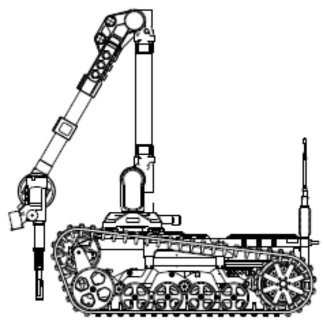


Fig. 5. Position of manipulator during maximum lift capacity test

Objective functions that are responsible for maximizing the robot's lifting capacity in selected tasks were constructed from the conditions of ensuring the possibility of transferring the load for individual joints and the condition of maintaining the stability of the robot's mobile platform. For example, for the fixed remaining parameters of the manipulator, Figures 6 and 7 show the lifting forces achieved by the manipulator at maximum reach depending on the length of the arm and shoulder, and the maximum lifting forces depending on the length of the arm and shoulder of the manipulator.

Observing the nature of the graphs, it can be noted that for different arm lengths, the maximum lifting force is limited by various restrictions. In Figure 7, it can be seen that for some configurations, the lifting force was zero. This is how the configurations were assessed in the case when the manipulator was too weak to lift the object or with a given combination of parameters the manipulator could not reach the object.

For the mentioned objective functions, a multi-criteria optimization of the parameters describing the configuration of the manipulator stored in the *Man_config* vector was carried out, assuming additional constraints:

- the manipulator mass cannot exceed the assumed limit of 15 kg;
- the first joint actuator of the manipulator (with the vertical axis) must carry the load that results from moving along a ramp with a lateral inclination of 30 degrees with the manipulator fully extended, with the maximum load that can be transferred by the remaining degrees of freedom;
- the lengths of the links must allow for the configuration of the load to be lifted at a predetermined distance from the front of the mobile platform to a certain height. (The position of the robot's manipulator during this task is shown in Fig. 5.);
- the lengths of the links allow taking a position that allows to inspect and pick up the load from under the car (Fig. 4a);
- the lengths of the links allow for inspection and taking the load through the passenger car window.

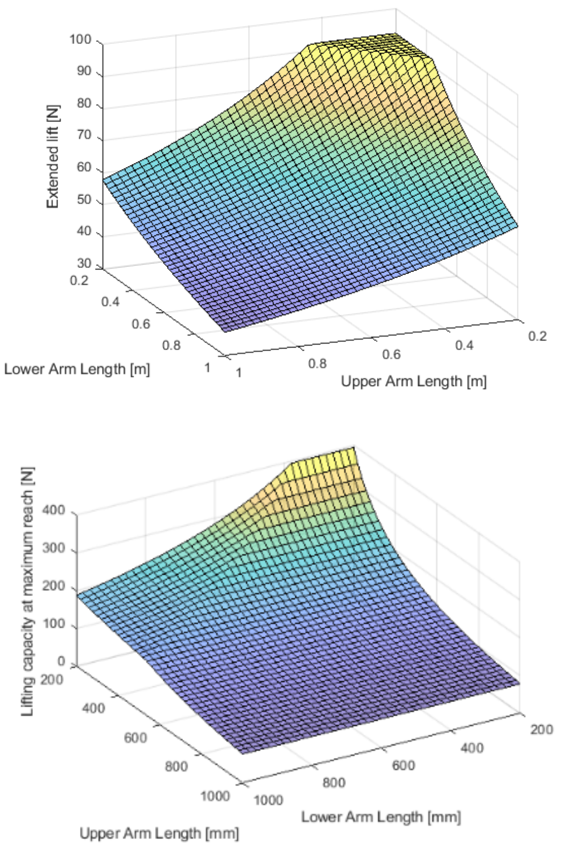


Fig. 6. Lifting capacity at maximum reach depending on the shoulder and arm lengths for selected configurations of the manipulator

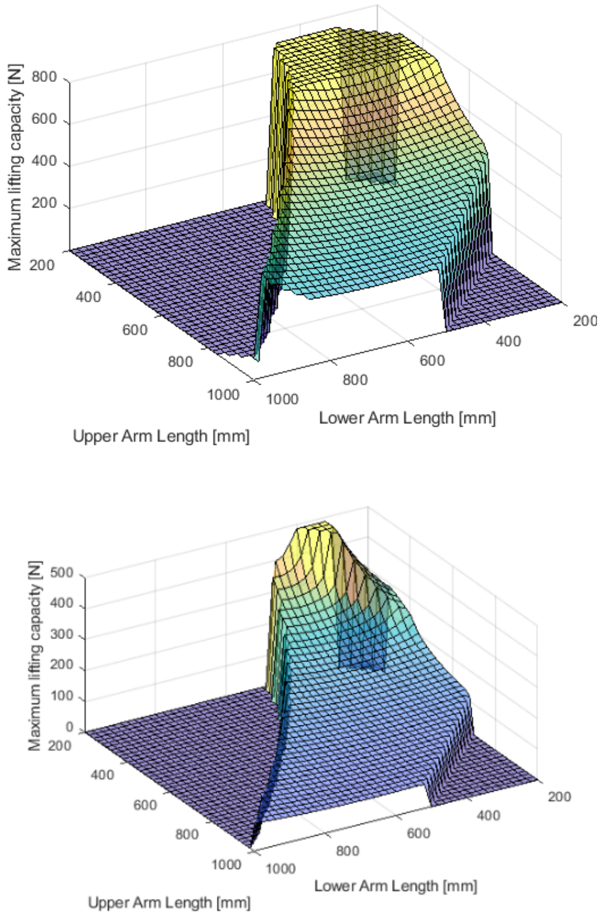


Fig. 7. Maximum lifting capacity depending on the shoulder and arm lengths for selected configurations of the manipulator

In figure 8, the objective functions and constraints are summarized.

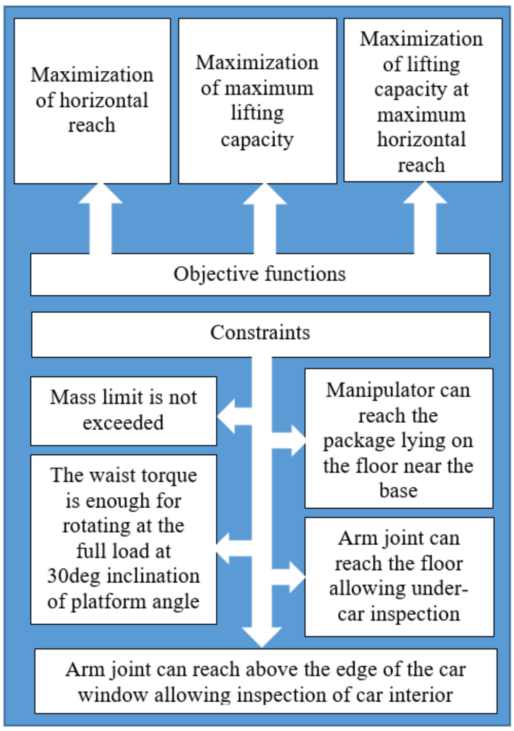


Fig. 8. Summary of objective functions and constraints used in optimization

3. Calculations and Results

The multi-criteria optimization algorithm NSGA-II presented by K. Deb [15] as implemented in Matlab function *gamultiopt* [16] was used to select the manipulator parameters. The algorithm of the function is explained in Figure 9.

For the population size 2000, the algorithm after 206 generations achieved the calculation end criterion, which was to obtain the difference in the mean distance of the points belonging to the Pareto front below the assumed tolerance. The result obtained is a point cloud in 3-dimensional space that is difficult to visualize on paper. Figure 10 shows three different views of the same values of the fitness function for the final generation of the algorithm's operation.

It can be seen that the results are divided into groups of points distributed over the surfaces, which is particularly visible in Figure 10b. Figures 11a and 11b show groups of fitness functions values in where the torques transmitted by the arm of the manipulator are highlighted in color.

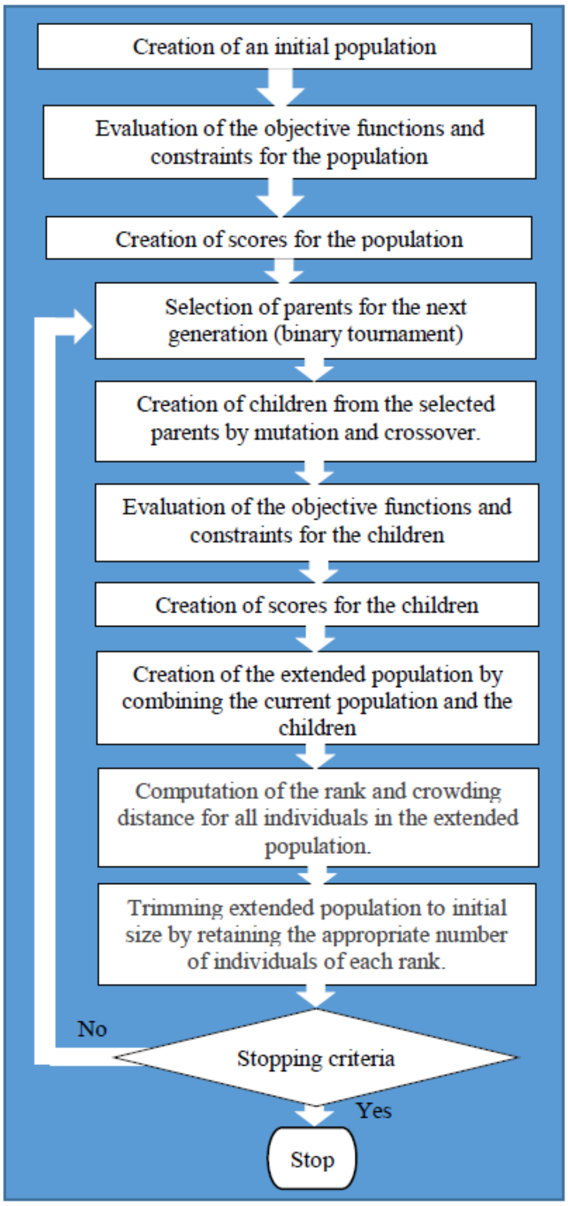


Fig. 9. Algorithm of Matlab gamultiopt function [16]

Particular groups of solutions are located on surfaces that group solutions according to the selected gear of the elbow and shoulder.

In Figure 11, it can be seen that in the final generation of results of the manipulator configurations, there are 3 sizes of joints in the elbow and 4 sizes in the shoulder.

Selected configurations and values of the fitness functions for solutions from the Pareto front are shown in Table 2.

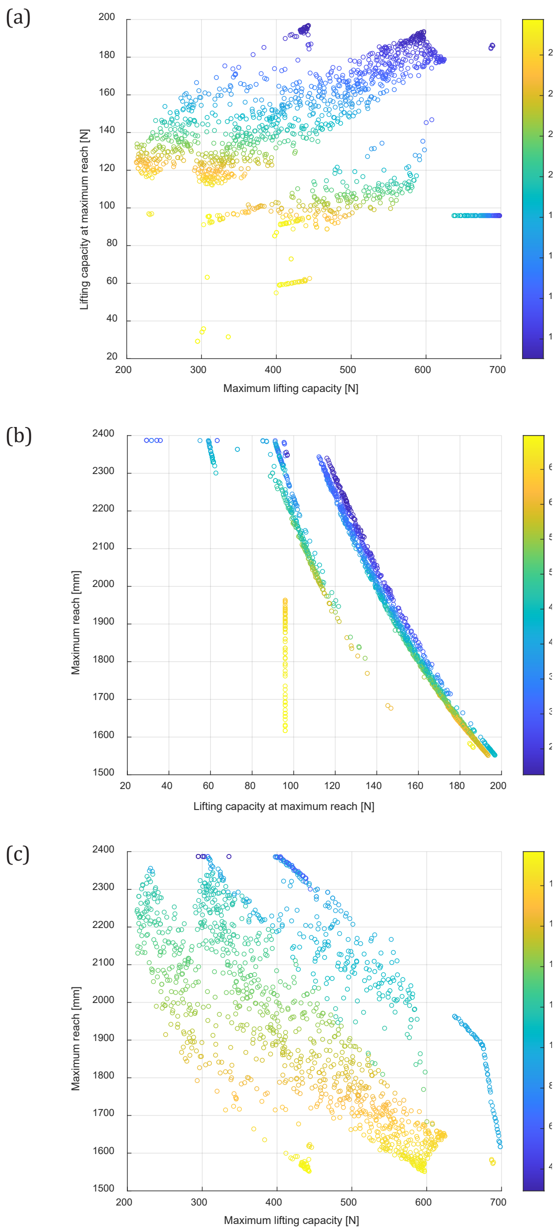
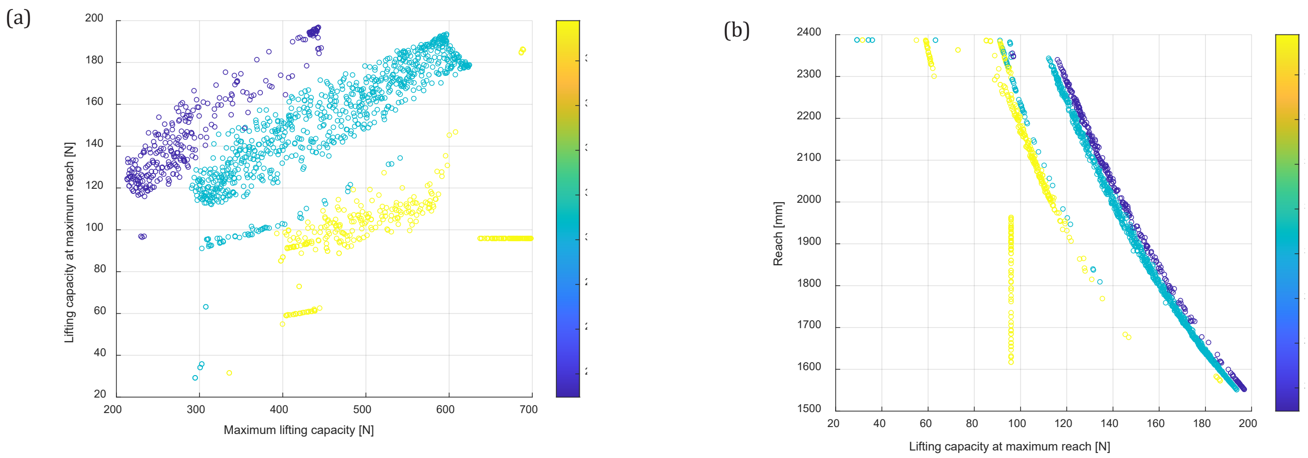


Fig. 10. Fitness functions values for the final generation of configurations

Table 2. Selected results from Pareto front

ID	Lifting capacity at maximum reach [N]	Maximum lifting capacity [N]	Horizontal reach [mm]	Maximum gripper torque [Nm]	Maximum arm torque [Nm]	Maximum shoulder torque [Nm]	Maximum waist torque [Nm]	Gripper length [mm]	Arm length [mm]	Shoulder length [mm]	Waist length [mm]	Mass [kg]
1	186	578	1602	79	306	398	230	396	523	683	211	14.1
2	178	599	1651	79	306	398	230	396	520	735	211	14.1
3	172	524	1703	79	306	398	230	396	581	726	211	14.2
4	166	528	1750	79	306	398	230	396	589	765	211	14.2
5	164	339	1800	79	230	398	230	396	658	746	211	13.5
6	155	431	1850	79	306	398	230	396	696	759	211	14.3
7	151	368	1902	79	306	398	230	396	791	715	211	14.4
8	148	307	1952	79	230	398	230	396	733	823	211	13.6
9	118	478	1983	79	306	306	230	396	689	899	211	13.5
10	140	399	2001	79	306	398	230	396	764	842	211	14.5
11	113	559	2004	79	398	306	230	396	737	871	211	14.5
12	111	466	2050	79	398	306	230	396	834	820	211	14.5
13	134	277	2103	79	230	398	230	396	816	891	211	13.8
14	102	469	2150	79	398	306	173	396	852	902	211	14.1
15	98	473	2201	79	398	306	173	396	861	943	211	14.1
16	123	229	2250	79	230	398	230	396	944	910	211	13.9
17	63	444	2301	38	398	230	173	396	917	988	211	12.9
18	89	422	2350	35	398	306	173	396	960	994	211	13.8
19	29	295	2387	153	306	173	230	396	992	999	211	13.2



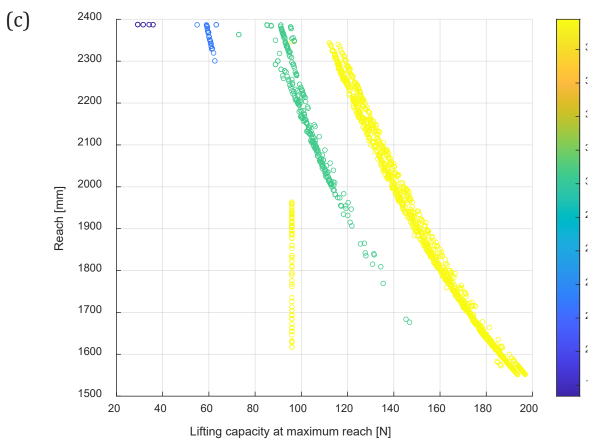


Fig. 11. Dependence of fitness functions on the shoulder and arm maximum torque

Figure 11b shows layers of points representing fitness functions values by the maximum torque capacity of the shoulder of the manipulator, which is coded by color. It can be noticed that there is a group of results that have constant lifting capacity at maximum reach. In this group of results, lifting capacity was limited by gripper torque.

It can be noticed that the best assessments of the fitness function of lifting capacity at the maximum reach are in the configurations in which the largest gears are in the shoulder joint, and the subsequent degrees of freedom are smaller and smaller.

For the fitness function responsible for maximizing the manipulator's lifting capacity, the best scores were given to configurations in which the gears driving the arm were as large or larger than the gears driving the shoulder. In the positions that the manipulator had to take when lifting heavier loads from the ground, the upper arm joint was the most loaded. It can also be seen that the masses of the manipulators in the proposed resulting configurations used almost the entire mass limit.

4. Conclusion

This adopted simple model allows for the initial assumption of design parameters for the manipulator that meets the functional requirements and mass limitations. The adopted method of selecting parameters allowed for the maximum use of the available mass limit to improve the functionality of the manipulator. One of the solutions that can be considered is, for example, a manipulator ID 10 shown in Table 2. It allows to lift up to 14 kg at a maximum extension of 2 m from the vertical axis of the manipulator and can lift a maximum of 40 kg at a distance of 0.5 m from the front edge of the platform. When, for similar reach, maximum capacity is more important than the load capacity at the maximum reach, solution ID 11 should be considered. It allows for lifting a maximum mass of 56kg at the expense of decreased lifting capability at maximum reach to 11 kg. To be able to draw correct conclusions from the analysis, it is important to correctly estimate the masses and torques transmitted by the joints and arms. Further work will focus on refining the model and taking into account other loads specified in the work, such as loads resulting from the use of additional robot accessories. It is also planned to take into account the influence of the selection of parameters on the vibrations of the manipulator resulting from the operation of the robot's drive system.

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