Grey Wolf Optimization Algorithm for Single Mobile Robot Scheduling

Milica Petrović and Zoran Miljković

***Abstract*—Development of reliable and efficient material transport system is one of the basic requirements for creating an intelligent manufacturing environment. Nowadays, intelligent mobile robots have been widely used as one of the components to satisfy this requirement. In this paper, a methodology based on Grey Wolf Optimization (GWO) algorithm is proposed in order to find the optimal solution of the nondeterministic polynomial-hard (NP-hard) single mobile robot scheduling problem. The performance criterion is to minimize total transportation time of the mobile robot while it performs internal transport of raw materials, goods, and parts in manufacturing system. The scheduling plans are obtained in Matlab environment and tested by Khepera II mobile robot system within a static laboratory model of manufacturing environment. Experimental results show the applicability and effectiveness of the developed intelligent approach in real world conditions.**

***Index Terms*—intelligent manufacturing system, scheduling, grey wolf optimization algorithm, optimization, mobile robot.**

I. Introduction

Motion planning and scheduling of an intelligent mobile robot is one of the most vital issues in the field of robotics. As a component of material transport system, an intelligent mobile robot with a particular kind of behavior exclusively developed for these purposes has been widely adopted in manufacturing systems. Having these facts in mind, this paper analyses integration and proposes a new methodology for solving single mobile robot scheduling problem.

Robot scheduling problem belongs to the class of NP-hard problems (see e.g. [1] and [2]), which has attracted interest of researchers in recent decades. Numerous efforts have been made in order to optimize single mobile robot scheduling problem. In reference [3], the authors presented tabu search and probabilistic tabu search to solve the single vehicle pickup and delivery problem with time windows. The aim was to minimize the total distance traveled by the vehicle. Hurink and Knust [4] considered a single-machine scheduling problem in a job-shop environment where the jobs have to be transported between the machines by a single transport robot. They regarded the robot scheduling problem as a generalization of the traveling salesman problem with time windows and used a local tabu search algorithm to solve it. The objective was to determine a sequence of all operations and corresponding starting times in such a way that all generalized precedence relations are respected and the sum of all traveling and waiting times is minimized. In reference [5], the authors proposed two different approaches to integrate a transportation stage into procedures for machine scheduling. For both approaches, a tabu search methods to calculate heuristic solutions for the considered problem was presented. Besides transportation times, the authors additionally considered empty moving times of the robot. The objective was to determine a schedule with minimal makespan. The problem of finding optimal feeding sequence in a manufacturing cell with feeders fed by a mobile robot with manipulation arm was investigated in [6], [7], [8], [9], [10] and [11]. Mathematical model for scheduling of single mobile robot in an impeller production line was given in [6]. References [7] and [8] focused on modeling and scheduling of autonomous mobile robot called „Little Helper” for a real-world industrial application. A genetic algorithm-based heuristic developed to find the near optimal solution for the robotic cell scheduling problem was presented in [9], [10], and [11].

In this paper, a methodology for intelligent material transport by using a single mobile robot is presented. We consider integrated process planning and scheduling (IPPS) problem where the parts have to be transported between the machines by a single mobile robot. IPPS problem with transportation times and a single robot may be formulated as follows: We are given *m* machines and *n* parts. Each part consists of operations which have to be processed in order defined by flexible process plan network. One machine tool on which the operation has to be processed is selected for each operation. Each machine can process at most one operation at a time. Additionally, transportation times between machines are considered. We assume that all these transport tasks have to be done by a single mobile robot which can handle at most one part at a time. The optimization objective is to determine a feasible schedule which minimizes the transportation time of the mobile robot. In order to find optimal solution, Grey Wolf Optimization (GWO) algorithm is proposed. According to the authors' best knowledge, it is the first implementation of GWO algorithm for mobile robot scheduling problem. Encoding/decoding scheme for the problem is presented and the implementation procedure of the proposed optimization algorithm is described. Scheduling plans obtained by the proposed methodology are tested by Khepera II mobile robot using a laboratory model of manufacturing environment.

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The remainder of the paper is organized as follows. In Section 2 we describe a problem of single mobile robot scheduling. Mathematical model and optimization objectives are formulated in Section 3. Grey Wolf Optimization algorithm and its implementation are briefly outlined in Section 4. Section 5 shows computational results and Section 6 gives concluding remarks. Finally, acknowledgement and references are stated at the end of the paper.

II. Problem Formulation

In this paper, we used integrated process planning and scheduling (IPPS) problem where the parts given in Fig. 1 have to be transported between the machines by a single mobile robot.

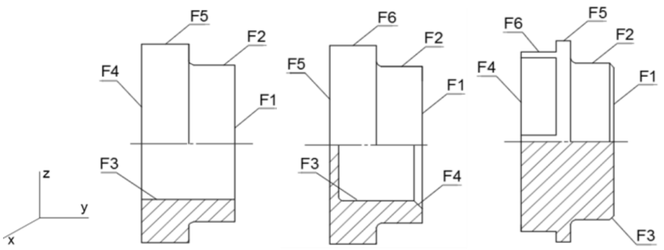

Fig. 1. The three representative sample parts with features.

According to defined scheduling plan (see Section 4), the robot will retrieve the part from the storage or machine tool, transport it to appropriate machine tool, and then return to another machine tool or storage. Operation order for three sample parts manufactured in considered manufacturing system is defined by flexible process plan network. Furthermore, the technical specification of parts including alternative operations, alternative machines, alternative tools, alternative TADs are also given in details in flexible process plan networks (Fig. 2) and corresponding processing times are given in Table 1.

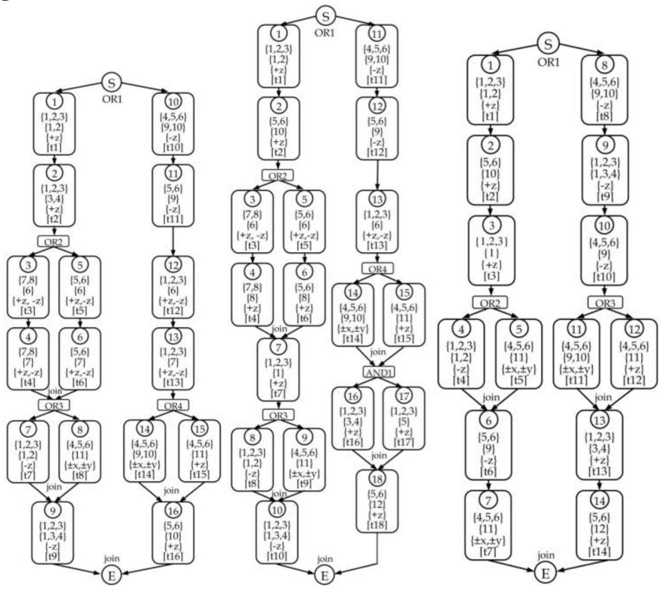

Fig. 2. Flexible process plan networks for sample part 1, part 2 and part 3.

TABLE I
Processing Times

part 1	t1 = [2.3, 3.3, 4.6, 6.5, 3.8, 5.5];
	t2 = [1.2, 1.0, 1.9, 1.5, 2.0, 1.6] ; t3 = [5.5, 3.8];
	t4 = [4.8, 8.1]; t5 = [3.3, 3.4]; t6 = [10.7, 24.1];
	t7 = [2.3, 3.3, 4.6, 6.5, 3.8, 5.5]; t8 = [5.7, 4.2, 2.8];
	t9 = [0.5, 0.7, 0.4, 1.0, 1.4, 0.8, 0.8, 1.1, 0.7];
	t10 = [2.7, 2.8, 2.9, 2.4, 2.8, 2.5]; t11 = [4.6, 7.2];
	t12 = [3.3, 4.8, 3.3]; t13 = [13.4, 26.6, 30.2];
	t14 = [2.7, 2.8, 2.9, 2.4, 2.9, 2.4];
	t15 = [5.7, 4.2, 2.8]; t16=[3.1, 3.2];

part 2	t1 = [2.3, 3.3, 4.6, 6.5, 3.8, 5.5]; t2 = [3.1, 3.2];
	t3 = [5.5, 3.8]; t4 = [34.3, 13.7]; t5 = [3.3, 3.4];
	t6 = [30.2, 13.4]; t7 = [0.7, 0.8, 0.9];
	t8 = [2.3, 3.3, 4.6, 6.5, 3.8, 5.5]; t9 = [5.7, 4.2, 2.8];
	t10 = [0.5, 0.7, 0.4, 1.0, 1.4, 0.8, 0.8, 1.1, 0.7];
	t11 = [2.7, 2.8, 2.9, 2.4, 2.8, 2.5];
	t12 = [4.6, 7.2]; t13 = [3.3, 4.8, 3.3];
	t14 = [2.7, 2.8, 2.9, 2.4, 2.9, 2.4]; t15 = [5.7, 4.2, 2.8];
	t16 = [1.2, 1.0, 1.9, 1.5, 2.0, 1.6]; t17 = [1.1, 1.5, 1.8];
	t18 = [0.5, 0.6];

part 3	t1 = [2.3, 3.3, 4.6, 6.5, 3.8, 5.5];
	t2 = [3.1, 3.2]; t3 = [0.6, 0.7, 0.8];
	t4 = [2.3, 3.3, 4.6, 6.5, 3.8, 5.5]; t5 = [5.7, 4.2, 2.8];
	t6 = [4.6, 7.2]; t7 = [10.8 , 9.7, 7.4];
	t8 = [2.7, 2.8, 2.9, 2.4, 2.8, 2.5];
	t9 = [0.5, 0.7, 0.4, 1.0, 1.4, 0.8, 0.8, 1.1, 0.7];
	t10 = [4.3, 3.5, 6.8]; t11 = [2.7, 2.8, 2.9, 2.4, 2.9, 2.4];
	t12 = [5.7, 4.2, 2.8]; t13 = [1.2, 1.0, 1.9, 1.5, 2.0, 1.6];
	t14 = [0.4, 0.5];

III. Objective Function

In this research, the single criterion used for selection of scheduling plans is based on transportation time. Transportation time (*TT*) is the time that mobile robot spent for transport of raw materials, goods, or parts between machine tools and can be computed as:

$$TT = \sum_{i=1}^{n-1} TTI((i, j_1), (i+1, j_2)) \tag{1}$$

where $TTI(i,j_1),(i+1,j_2)$ is the transportation time between the alternative machines j_1 and j_2 for two consecutive operations, and n is the (total) number of operations in scheduling plan.

Objective function used for the optimization of the mobile robot scheduling problem is calculated by using the following equation:

$$object = \min(\mathrm{TT}) \tag{2}$$

Furthermore, it is important to illustrate the following assumptions that need to be taken care of for mobile robot, machines and parts:

- the mobile robot can transport only one part at time,
- each machine can handle only one operation at the time,

- transportation time of the mobile robot between machines and processing times are known,
- only one machine for each operation can be selected,
- operations related to one part cannot be processed simultaneously,
- transport of part cannot start before operation is completed,
- operation of part cannot start before transport is completed.

IV. Grey Wolf Optimization algorithm

The Grey Wolf Optimization (GWO) algorithm belongs to new population based meta-heuristics originally proposed by Mirjalili et al. in [12]. It is inspired from the hunting behavior and the social hierarchy of grey wolves in nature. According to societal hierarchy, the grey wolves are categorized into four levels (alpha, beta, delta and omega). The alphas are the dominant because the group follows his/her instructions. The betas are the secondary wolves that assist the alphas in making decisions. Omega is the lowest ranking grey wolves. The alpha, beta, and delta estimate the victim position and update their positions randomly around the victim. The final position would be in a position within a circle which is defined by the positions of alpha, beta, and delta in the search space.

Mathematical model of the social hierarchy is described as follows. According to social hierarchy of wolves, the best fitness solution is defined as alpha (α). The second and third best solutions are beta (β) and delta (δ). The rest of the solutions are assumed to be omega (ω).

Mathematical model of encircling prey is given by the following equations:

$$D = \left| \vec{C} \cdot \vec{X}_p(\mathrm{t}) - \vec{X}(\mathrm{t}) \right| \tag{3}$$

$$\vec{X}(\mathrm{t}+1) = \vec{X}_p(\mathrm{t}) - \vec{\mathrm{A}} \cdot \vec{\mathrm{D}} \tag{4}$$

where t indicates iteration, $\vec{X}_p$ is the position vector of the prey, $\vec{X}$ is the position vector of a grey wolf, $\vec{A}$ and $\vec{C}$ are coefficient vectors calculated as follows:

$$\vec{A} = 2\vec{a} \cdot \vec{r}_1 - \vec{a} \tag{5}$$

$$\vec{C} = 2 \cdot \vec{r}_2 \tag{6}$$

where components of $\vec{a}$ linearly decreased from 2 to 0, and r_1 and r_2 are random vectors in [0,1].

Furthermore, mathematical model of hunting prey is given by the following equations:

$$D_\alpha = \left| \vec{C}_1 \cdot \vec{X}_\alpha - \vec{X} \right| \tag{7}$$

$$D_\beta = \left| \vec{C}_1 \cdot \vec{X}_\beta - \vec{X} \right| \tag{8}$$

$$D_\delta = \left| \vec{C}_1 \cdot \vec{X}_\delta - \vec{X} \right| \tag{9}$$

Finally, the positions of various categories of wolves (the first free best solutions) are given by the following formulas:

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1(\vec{\mathrm{D}}_\alpha) \tag{10}$$

$$\vec{X}_2 = \vec{X}_\beta - \vec{A}_2(\vec{\mathrm{D}}_\beta) \tag{11}$$

$$\vec{X}_3 = \vec{X}_\delta - \vec{A}_3(\vec{\mathrm{D}}_\delta) \tag{12}$$

$$\vec{X}(\mathrm{t}+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \tag{13}$$

The key objective of the development of optimization model for the single mobile robot scheduling problem is to generate an encoding/decoding scheme. This means that parameters of process plans and scheduling plans need to be incorporated into search agents of GWO algorithm. Feasible solution or schedule is encoded as search agent (grey wolf) presented in Fig. 3. Each search agent in scheduling string consists of five parts with different lengths. The first part of the search agent is an alternative process plan string. The second part of the search agent is a scheduling plan string. The third part of the search agent is the machine string. The fourth and fifth parts of the search agent are the tool string and the TAD string, respectively. Readers are referred to reference [13] for detailed description of each string.

Decoding procedure and fitness evaluation starts after encoding phase. Firstly, for each part in scheduling plan string information about machine and mobile robot status need to be obtained. For example, we will take into consideration the first three numbers of scheduling plan (2 1 2). The first number in scheduling plan is 2. It means that scheduling starts with part 2 and its first operation is performed on M5. After that follows the first operation of part 1 performed on M2. Finally, the second operation of part 2 is followed afterwards. In other words, taking transportation into account, it means that mobile robot transport part 2 to M5, then part 1 to M2, and part 2 to M5 afterwards. This decoding procedure is followed for all operations in scheduling plan. Finally, according to scheduling plan, path that mobile robot follows can be defined as:

M5→M2→M5→M5→M1→M2→M8→M2→M6→M5→ M8→M2→M2→M4→M1→M5→M5→M2→M6.

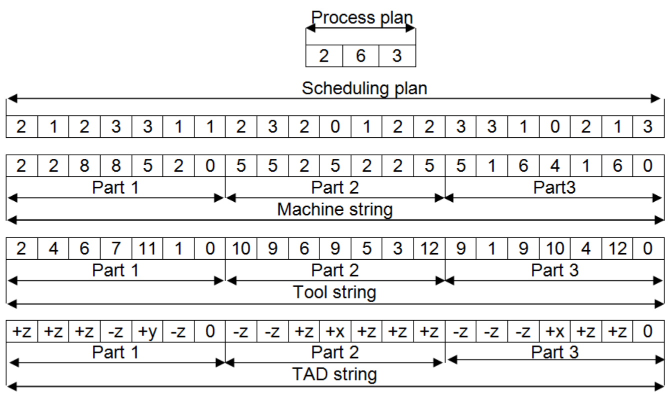

Fig. 3. Encoding scheme.

On the basis of behavior of grey wolves and encoding/decoding scheme, GWO is implemented as given in Algorithm 1. In this optimization algorithm, the positions of grey wolves are considered as different position variables (alternative solutions of machines, tools and TADs) and the distances of the prey from the grey wolves determine the fitness value of the objective function defined by (2). In GWO, the individual grey wolf adjusts its position and moves to the better position. The GWO saves the best solutions obtained through the course of iterations. The goal of this algorithm is to reach to the prey by the shortest possible route (optimal scheduling plan).

ALGORITHM I
PSEUDO CODE OF THE GWO ALGORITHM

1	**Initialize** GWO parameters (population size i.e. number of grey wolfs, maximum number of iterations, position vector X, and vectors A, a, C)
2	**Initialize** the grey wolf population
3	**Evaluate** the fitness of each search agent by (2). Based on the fitness value, three best wolves are identified as: X_α = the best search agent X_β = the second best search agent X_δ = the third best search agent
4	**Repeat:**
5	generate next population by updating the position of each search agent (10), (11), (12)
6	update a, A, C by using (5) and (6)
7	round off the real number of positions for machine, tool, and TAD to the nearest integer number from machine, tool and TAD sets
8	**evaluate** the fitness of each search agent
9	update X_α, X_β, X_δ
10	**Until** the maximum of generation is not met
11	**Output** the optimal scheduling plan as X_α

V. EXPERIMENTAL RESULTS

This section provides information related to experimental setup. The layout of the real existing manufacturing environment is used as laboratory model of a manufacturing environment. The transportation time between the machines are given in Table 2. The experimental platform is based on Khepera II mobile robot. Proposed algorithm is implemented in Matlab environment, which is used to control the robot as well. The proposed GWO algorithm is implemented in Matlab environment running on a desktop computer with a 3.10 GHz processor (2GB RAM). Parameters of GWO algorithm for single mobile robot scheduling are set as follows: the size of population is 100, the maximum number of iterations is 100, *a* linearly decreased from 2 to 0, and r_1 and r_2 are random vectors in [0, 1]. Gantt chart of experiment is given in Fig. 5, where minimal transportation time of the mobile robot is 33s. Convergence curves of GA, PSO and GWO algorithm are presented in Fig. 6 and the statistical results of algorithms are given in Fig. 8.

TABLE II
TRANSPORTATION TIME OF THE MOBILE ROBOT BETWEEN THE MACHINES [S]

Machine	1	2	3	4	5	6	7	8
1	0	4	8	10	12	5	6	14
2	4	0	3	7	11	5	4	6
3	8	3	0	5	7	9	8	4
4	10	7	5	0	4	14	12	6
5	12	11	7	4	0	18	12	10
6	5	5	9	14	18	0	6	8
7	6	4	8	12	12	6	0	3
8	14	6	4	6	10	8	3	0

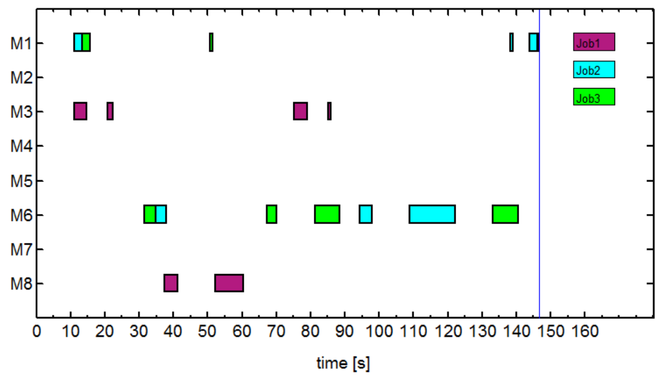

Fig. 5. Gantt chart for scheduling plan based on minimizing transportation time of mobile robot.

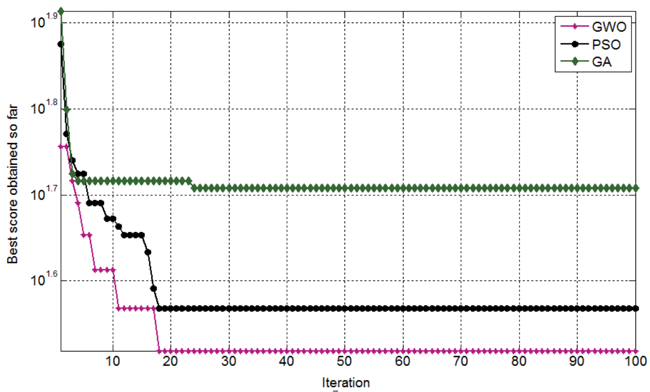

Fig. 6. Convergence curves of objective function.

Experimental verification by using Khepera II mobile robot is done for the scheduling plan from Fig. 5. The reproduced trajectory consists of the following machine tools: M3→M3→M8→M8→M3→M3→M1→M6→M6→M6→ M1→M1→M1→M1→M6→M1→M6→M6→M6. Mobile robot motion trajectory is carried out in a static laboratory model of manufacturing environment where positions of the machines are known a priori. While executing the transport task, the robot uses the methodology presented in [14], [15] and [16] to determine its pose. Fig. 7 shows the Khepera II mobile robot during the transport task between the following machines: M3→M8→M3→M1→M6→M1→M6→M1→M6.

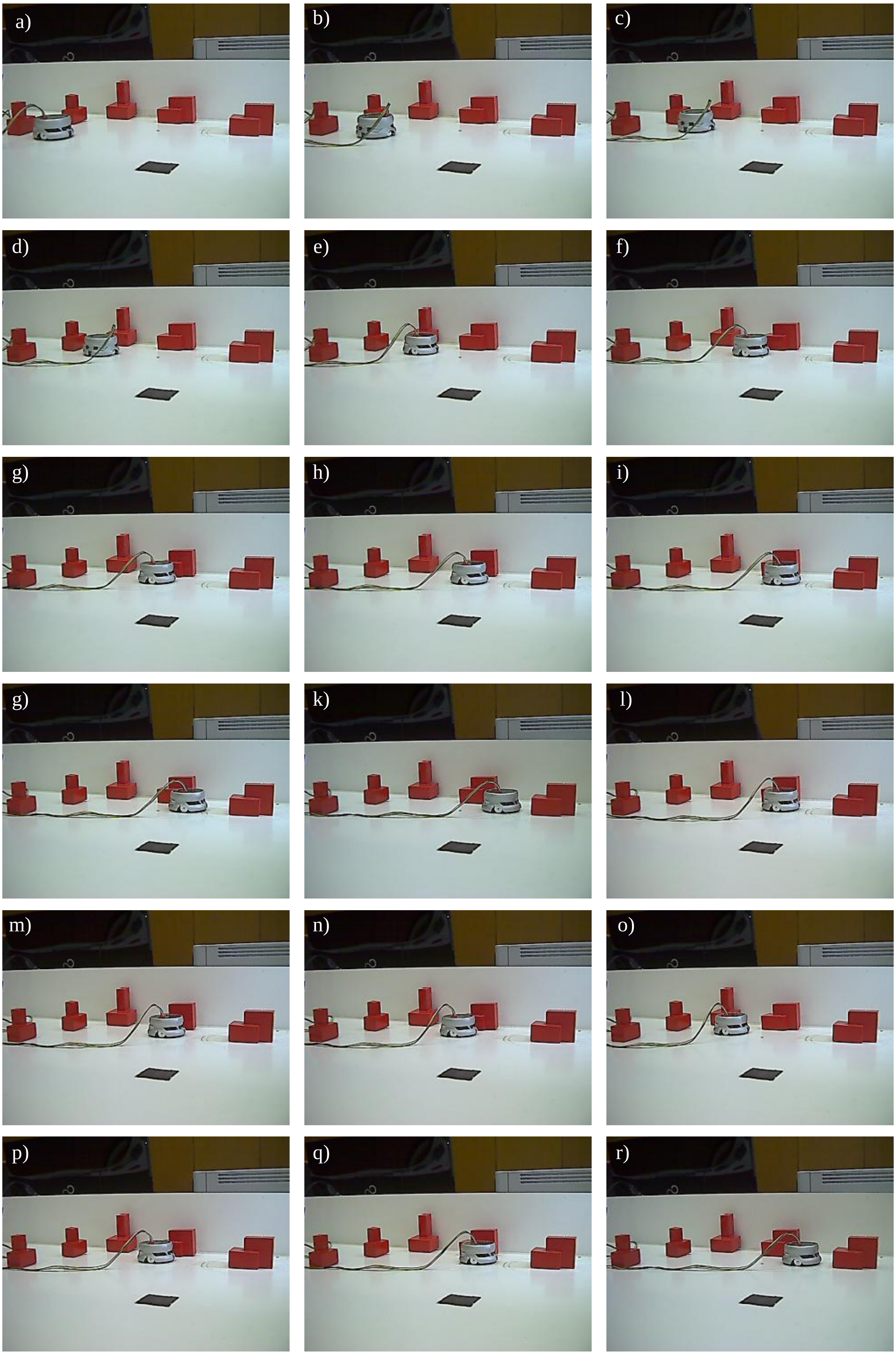

Fig. 7. Mobile robot motion in laboratory model of manufacturing environment.

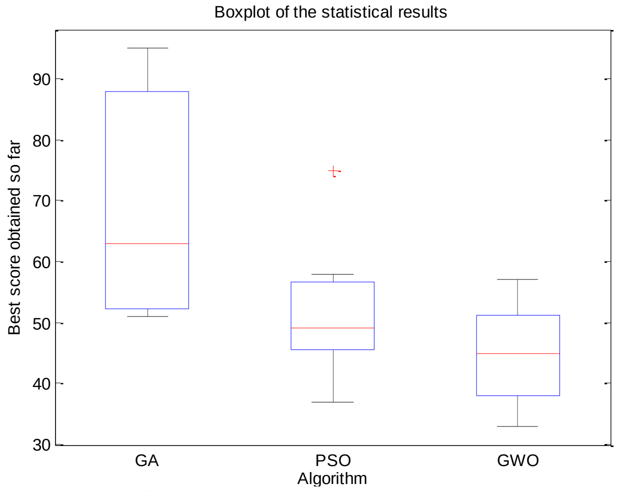

Fig. 7. Boxplot of the statistical results.

VI. Conclusion

Implementation of intelligent mobile robot into a manufacturing environment and its scheduling has been gaining popularity in research community over the recent years. In this paper, a new biologically-inspired method based on the Grey Wolf Optimization (GWO) algorithm is proposed to optimize combinatorial NP-hard single mobile robot scheduling problem. The optimal schedule sequence is the result of the single-objective optimization procedure and it is found based on minimum transportation time of the mobile robot as criteria. The network representation for three sample parts is adopted to describe machine flexibility, tool flexibility, TAD flexibility, process flexibility as well as sequence flexibility. According to flexible process plans network and information about alternative manufacturing resources, solutions of the scheduling problem are encoded into searching agents in order to intelligently search for the optimal sequence of mobile robot transportation tasks.

The performance of the presented GWO algorithm is verified and evaluated compared with the results obtained using GA and PSO algorithm. All the algorithms were developed in the Matlab environment and implemented on the Khepera II mobile robot. The experimental results indicate that GWO algorithm achieves better performance than other biologically inspired meta-heuristic algorithms. Also, the experimental results show that an intelligent mobile robot, with a priori known static obstacles in the environment, has the ability to generate an optimal motion path in accordance with the requirements of the manufacturing process and servicing priority of machine tools. Since GWO algorithm has shown a significant improvement in the performance of manufacturing system, the multi-objective mobile robot scheduling problem can be considered as one of the main possible future directions in this field.

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