A Supervisory Control-Based Navigation Architecture for Multiple Autonomous Robots in Industry 4.0 Environments^{*}

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Abstract: The industry 4.0 paradigm is usually associated with large factories with several smart machines that demand a powerful and versatile connectivity infrastructure. In this context, a single robot is seldom able to deal with the logistics of an entire factory, being necessary the use of multiple robots. Thus, in this paper we extend the DES-based navigation architecture for a single robot, previously proposed in Gonzalez et al. (2018), to deal with multiple mobile robots.

Keywords: Discrete Event Systems, Mobile Robots, Industry 4.0, Supervisory Control.

1. INTRODUCTION

In recent years, a new concept of industry, called Industry 4.0 (Gilchrist, 2016), has emerged and is currently adopted to denominate the trends of automation and data exchange in manufacturing technologies, in the context of “smart factories” (Wang et al., 2016). Some of the main fundamentals of Industry 4.0 are cyber-physical systems (Jirkovsky et al., 2017), internet of things (Da Xu et al., 2014), and mobile robots (Kehoe et al., 2015).

The Discrete Event System (DES) formalism has been proved suitable to deal with mobile robot navigation. In Roszkowska (2002), a DES-based supervisory controller that ensures collision and deadlock avoidance for a group of robots is proposed. In Košecká and Bajcsy (1994), automaton-based models for mobile robot navigation were used to show the viability of using DES theory in the modeling, analysis, and synthesis of behaviors applied to the navigation of a mobile robot. Structures for representing the environment and some specifications were presented in Iqbal et al. (2012). In Fabre and Jezequel (2009), the path planning problem to decentralized systems with action costs was addressed by using several weighted automata. In Kloetzer and Mahulea (2016), a formal method based on Linear Temporal Logic (LTL) has been employed to describe and model specifications in mobile robot navigation. A formal synthesis of supervisory control software for multiple robot systems was developed in Hill and Lafortune (2017). In Gonzalez et al. (2018) a DES-based navigation architecture for a single-robot in Industry 4.0 environments was introduced. In Tatsumoto et al. (2018) an online supervisory control approach based on limited lookahead policy for multiple robots navigation

was presented. In Dulce-Galindo et al. (2019) and in Basile et al. (2019), multiple robots navigation systems were proposed, with a clear focus on task assignment algorithms. The approach proposed in Dulce-Galindo et al. (2019) is centralized and automaton-based, while the one proposed in Basile et al. (2019) is decentralized (auction-based) and colored modified hybrid petri net-based.

The industry 4.0 paradigm is usually associated with large factories with several smart machines that demand a powerful and versatile connectivity infrastructure. Thus, in this context, a single robot is seldom able to deal with the logistics of a entire factory, being necessary the use of multiple robots. In order to circumventing the single-robot limitation of the navigation architecture proposed in Gonzalez et al. (2018), in this paper, we extend the DES-based navigation proposed there to deal with multiple mobile robots.

2. BACKGROUND PRELIMINARIES

Let $G = (X, \Sigma, f, \Gamma, x_0, X_m)$ denote a deterministic finite automaton that models a Discrete Event System (DES), where X is the finite set of states, Σ is the finite set of events, $f : X \times \Sigma \rightarrow X$ is the transition function, partially defined over its domain, function $\Gamma : X \rightarrow 2^\Sigma$ (where 2^Σ denotes the power set of Σ) determines the set of active events of the states of G , i.e., $\Gamma(x) = \{\sigma \in \Sigma : f(x, \sigma) \text{ is defined}\}$, x_0 is the initial state, and X_m is the set of marked states. Throughout the text, Σ^* denotes the Kleene closure of Σ , which is the set of all finite strings formed by events in Σ including the empty string, denoted by ε . The transition function f is extended to $f : X \times \Sigma^* \rightarrow X$ in the following manner: $f(x, \varepsilon) = x$ and $f(x, s\sigma) = f(f(x, s), \sigma)$, for all $x \in X$, $s \in \Sigma^*$ and $\sigma \in \Sigma$. The languages generated and marked by G are, respectively, $L(G) = \{s \in \Sigma^* : f(x_0, s) \text{ is defined}\}$ and $L_m(G) = \{s \in L(G) : f(x_0, s) \in X_m\}$. The prefix-closure

^{*} This work has been supported in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Finance Code 001, and the Brazilian Research Council (CNPq), grant number 309.652/2017-0.

of a language L is defined as $\bar{L} = \{s \in \Sigma^* : (\exists t \in \Sigma^*)[st \in L]\}$, and, if $L = \bar{L}$, L is said to be prefix-closed.

Let Σ_s and Σ_l be two sets of events such that $\Sigma_s \subseteq \Sigma_l$. The natural projection (Ramadge and Wonham, 1989) from Σ_l^* to Σ_s^* is a function that removes from strings in Σ_l^* those events that are not in Σ_s , and is denoted as $P : \Sigma_l^* \rightarrow \Sigma_s^*$. The inverse projection P^{-1} is the function that recovers those strings in Σ_l^* that generate a given projection in Σ_s^* , being formally defined as $P^{-1}(t) = \{s \in \Sigma_l^* : P(s) = t\}$. The projection and the inverse projection operations are both extended to languages by applying P and P^{-1} to all strings in the language.

The accessible and coaccessible parts of an automaton G are denoted by $Ac(G)$ and $CoAc(G)$, respectively, and the parallel composition between two automata G_1 and G_2 is denoted as $G_1 \parallel G_2$. The languages generated and marked by $G_1 \parallel G_2$ are, respectively, $L(G_1 \parallel G_2) = P_1^{-1}[L(G_1)] \cap P_2^{-1}[L(G_2)]$ and $L_m(G_1 \parallel G_2) = P_1^{-1}[L_m(G_1)] \cap P_2^{-1}[L_m(G_2)]$, where $P_i : (\Sigma_1 \cup \Sigma_2)^* \rightarrow \Sigma_i^*$, for $i = 1, 2$ (Cassandras and Lafortune, 2008, chap. 2).

The supervisor is a mapping $S : L(G) \rightarrow 2^\Sigma$, where, for a given string $s \in L(G)$, $\Gamma[f(x_0, s)] \cap S(s)$ are the events that are enabled by S at state $f(x_0, s)$ of G . The set of events Σ is partitioned as $\Sigma = \Sigma_c \dot{\cup} \Sigma_{uc}$, where Σ_c and Σ_{uc} are, respectively, the sets of controllable events and uncontrollable events. In this regard, we say that a supervisor is admissible if for all $s \in L(G)$, $\Gamma[f(x_0, s)] \cap \Sigma_{uc} \subseteq S(s)$. The language achieved by the closed-loop system S/G is, therefore, recursively characterized as: (i) $\varepsilon \in L(S/G)$, and (ii) $s\sigma \in L(S/G) \Leftrightarrow s \in L(S/G) \wedge s\sigma \in L(G) \wedge \sigma \in S(s)$. The language marked by the closed-loop system is equal to the part of $L_m(G)$ that remains after the supervisory control action, i.e. $L_m(S/G) = L(S/G) \cap L_m(G)$. A supervisor is said to be nonblocking if $L(S/G) = \bar{L}_m(S/G)$.

A realization of a supervisor S is an automaton $R = (X_r, \Sigma, f_r, \Gamma_r, x_{0_r}, X_r)$ whose states are all marked, and is such that, for all $s \in L(G)$, $S(s) = \Gamma_r[f_r(x_{0_r}, s)]$. Thus, the closed-loop behavior is characterized by $R \parallel G$, since $L(S/G) = L(R \parallel G)$ and $L_m(S/G) = L_m(R \parallel G)$.

A language $K \subseteq L(G)$ is controllable with respect to $L(G)$ and Σ_{uc} if $\bar{K}\Sigma_{uc} \cap L(G) \subseteq \bar{K}$, and it is said to be closed with respect to $L_m(G)$ (or $L_m(G)$ -closed) if $K = \bar{K} \cap L_m(G)$. For a given language $K \subseteq L_m(G)$, there exists a nonblocking supervisor S such that $L_m(S/G) = K$ if, and only if, K is controllable and $L_m(G)$ -closed.

The applicable language requirement K is frequently given as the intersection of two (or more) elementary specification languages, i.e., $K = K_1 \cap K_2$, where $K_1, K_2 \subseteq L_m(G)$. In this case, we can investigate the possibility of synthesizing nonblocking supervisors S_1 and S_2 such that $L_m(S_1/G) = K_1$ and $L_m(S_2/G) = K_2$, and thus, construct the modular control architecture where modular supervisor $S_1 \wedge S_2$ is obtained by computing the conjunction of S_1 and S_2 , i.e., for all $s \in L(G)$, $S_1 \wedge S_2(s) = S_1(s) \cap S_2(s)$. As a consequence, $L_m(S_1 \wedge S_2/G) = K_1 \cap K_2$. Moreover, supervisor $S_1 \wedge S_2$ is nonblocking if, and only if, languages K_1 and K_2 are nonconflicting, i.e., $\bar{K}_1 \cap \bar{K}_2 = \bar{K}_1 \cap K_2$.

3. PROBLEM FORMULATION

In this section, we propose the robot navigation problem in Industry 4.0 environments to be addressed in this paper, which extends the single-robot navigation problem considered in Gonzalez et al. (2018) to a case with multiple robots. As in Gonzalez et al. (2018), we consider that the environment is represented by an automaton model, as will be described in Subsection 3.1. In Subsection 3.2, we formally present the multi-robot navigation problem in Industry 4.0 environments.

3.1 The Environment Automaton Model G_e

The environment where the robot navigation is performed is represented by an automaton $G_e = (X_e, \Sigma_e, f_e, \Gamma_e, x_{0_e}, X_{m_e})$, whose states in X_e represent all possible positions and orientations (poses) a robot can assume, Σ_e is the set of command events that correspond to those movements that connect the poses in X_e , the transition function f_e and the set of active events Γ_e are defined according to the environment connectivity. Finally, in order to compute a path to be followed by a mobile robot, x_{0_e} is defined as the pose of that robot at the beginning of the task and X_{m_e} is defined as the set of states that represent the complete execution of its task (Gonzalez et al., 2018).

Let $x_1, x_{n+1} \in X_e$. A path in automaton G_e that takes the robot from state x_1 to state x_{n+1} has the form $x_1\sigma_1x_2\sigma_2x_3\ldots\sigma_nx_{n+1}$, where, $\forall k \in \{1, \dots, n\}$, $x_k \in X_e$, $\sigma_k \in \Sigma_e$ and $f_e(x_k, \sigma_k) = x_{k+1}$. Notice that there may exist several different paths that connect state x_1 to state x_{n+1} , and each of them is characterized by its corresponding string of command events $\sigma_1\sigma_2\ldots\sigma_n \in \Sigma_e^*$. In order to compare different paths, we define the weight function

$$w : \Sigma_e \rightarrow R_+, \quad \sigma \mapsto w(\sigma) = c, \quad (1)$$

where c represents the cost of executing the robot movement corresponding to command event σ . We, then, define the cost of executing a string $s = \sigma_1\sigma_2\ldots\sigma_n \in \Sigma_e^*$ as follows:

$$J(s) = \sum_{i=1}^n w(\sigma_i). \quad (2)$$

Example 1. Consider the hypothetical industrial environment initially introduced in Gonzalez et al. (2018) and depicted in Figure 1, which resembles a smart factory composed by a conveyor belt ①, which is a loading and unloading terminal, shelves ⑤ and ⑥ that are used to store raw materials and parts processed either by the computer numerically controlled (CNC) milling machine ⑦ or the painting machines ② and ③. The robot arm ④ is used either to transfer parts from one paint machine to the other, or to reject those painted parts that do not meet some quality standard to the orange rectangle. Notice that a mobile robot must be at pose M_i to interact with element ②, $i = 1, \dots, 7$.

The automaton that models this environment is $G_e = (X_e, \Sigma_e, \Gamma_e, x_{0_e}, X_{m_e})$, where (i) $X_e = X_{int} \dot{\cup} X_{ps}$ with $X_{int} = \{1, 2, 3, \dots, 32\}$ and $X_{ps} = \{M_1, M_2, M_3, \dots, M_7\}$ are formed with those poses that correspond to the corridor intersections and those poses that allow the robot to pick and store parts, respectively, (ii) Σ_e , formed by the

Figure 1. Map of the environment. The arrows represent the possible robot poses (states of automaton G_e): the tail indicates the positional coordinate and the direction corresponds to the robot orientation.

events listed in Table 1, (iii) $\Gamma_e : X_e \rightarrow 2^{\Sigma_e}$, presented in Table 2 for all $x \in X_e$; (iv) f_e , defined, for each state $x \in X_e$, according to the active events presented in Table 2 — for example, for $x = 1$, transition function f_e is defined for events $m4.5$, $t180$, $t90$ and $t90^-$, and, as it can be seen, with the help of Figure 1, $f_e(1, m4.5) = 9$, since command event $m4.5$ models a 4.5m forward movement, $f_e(1, t180) = 3$, since command event $t180$ corresponds to a 180° rotational movement, and $f_e(1, t90) = 2$ (resp. $f_e(1, t90^-) = 4$) since command event $t90$ (resp. $t90^-$) is associated with a 90° counterclockwise (resp. clockwise) rotational movement, and; (v) x_{0_e} and X_{m_e} , respectively, which are defined by the planner at each task assigned to a robot.

The values of the weight function w are listed in the third column of Table 1, being defined as follows: (i) $w(md) = d + 0.01$, where $d \in \{0.75, 4.5, 9.0\}$ is the distance to be traveled; (ii) $w(t\theta) = |\theta|/200 + 0.01$, where $\theta \in \{90, 180\}$ is the rotation angle, and; (iii) $w(sm_k) = \sum_i (|\theta_i|/200 + 0.01) + \sum_j (d_j + 0.01)$, $k = 1, 2, \dots, 13$, where θ_i (resp. d_j) are all rotational (resp. translational) movements present in sm_k . □

3.2 Multi-robot Navigation Problem

We address, in this paper, the problem of the navigation of multiple mobile robots in an industrial environment modeled by an automaton G_e together with a cost function (function J , defined in Equation (2)). The following robot tasks are considered:

- Task 1. This task is completed when the robot reaches some state (pose) belonging to a set $X_{goal} \subseteq X_e$;
- Task 2. This task is completed after the robot visits all states (pose) belonging to a set $X_{goal} \subseteq X_e$.

Since the robot is required to visit only one state in X_{goal} when it executes Task 1, it is necessary to determine the path starting at the current state of the robot and ending

Table 1. Environment automaton events Σ_e .

Event	Description	$w(\cdot)$
$m0.75$	move robot 0.75m	0.76
$m4.5$	move robot 4.5m	4.51
$m9.0$	move robot 9.0m	9.01
$t90$	turn robot 90° (counterclockwise)	0.46
$t90^-$	turn robot -90° (clockwise)	0.46
$t180$	turn robot 180°	0.91
$sm1$	turn robot 180° and move 0.75m	1.67
$sm2$	move 1.5m, turn 90° and move 0.75m	2.73
$sm3$	move 1.5m, turn -90° and move 0.75m	2.73
$sm4$	move 2.25m, turn 90° and move 0.75m	3.48
$sm5$	move 2.25m, turn -90° and move 0.75m	3.48
$sm6$	move 3.00m, turn 90° and move 0.75m	4.23
$sm7$	move 3.00m, turn -90° and move 0.75m	4.23
$sm8$	turn 180°, move 0.75m, turn 90° and move 1.5m	3.64
$sm9$	turn 180°, move 0.75m, turn -90° and move 1.5m	3.64
$sm10$	turn 180°, move 0.75m, turn 90° and move 2.25m	4.39
$sm11$	turn 180°, move 0.75m, turn -90° and move 2.25m	4.39
$sm12$	turn 180°, move 0.75m, turn 90° and move 3.00m	5.14
$sm13$	turn 180°, move 0.75m, turn -90° and move 3.00m	5.14

Table 2. Active events of the states of G_e .

X_e	Γ_e	X_e	Γ_e
1	$\{t90, t90^-, t180, m4.5\}$	21	$\{t90, t90^-, t180\}$
2	$\{t90, t90^-, t180\}$	22	$\{t90, t90^-, t180\}$
3	$\{t90, t90^-, t180\}$	23	$\{t90, t90^-, t180, m4.5, sm4\}$
4	$\{t90, t90^-, t180, m9.0\}$	24	$\{t90, t90^-, t180, m4.5\}$
5	$\{t90, t90^-, t180, m4.5\}$	25	$\{t90, t90^-, t180\}$
6	$\{t90, t90^-, t180, m9.0\}$	26	$\{t90, t90^-, t180, m4.5\}$
7	$\{t90, t90^-, t180, m0.75\}$	27	$\{t90, t90^-, t180, m4.5, sm5\}$
8	$\{t90, t90^-, t180\}$	28	$\{t90, t90^-, t180, m4.5\}$
9	$\{t90, t90^-, t180, m4.5, sm5\}$	29	$\{t90, t90^-, t180\}$
10	$\{t90, t90^-, t180\}$	30	$\{t90, t90^-, t180, m4.5\}$
11	$\{t90, t90^-, t180, m4.5\}$	31	$\{t90, t90^-, t180, m4.5\}$
12	$\{t90, t90^-, t180, m4.5, sm3\}$	32	$\{t90, t90^-, t180\}$
13	$\{t90, t90^-, t180, m4.5, sm4\}$	M_1	$\{sm1\}$
14	$\{t90, t90^-, t180, m4.5, sm6\}$	M_2	$\{sm8, sm11\}$
15	$\{t90, t90^-, t180, m0.75\}$	M_3	$\{sm1\}$
16	$\{t90, t90^-, t180, m4.5, sm6, sm7\}$	M_4	$\{sm9, sm12\}$
17	$\{t90, t90^-, t180, m4.5\}$	M_5	$\{sm10, sm11\}$
18	$\{t90, t90^-, t180, m4.5, sm2, sm3\}$	M_6	$\{sm10, sm11\}$
19	$\{t90, t90^-, t180, m4.5\}$	M_7	$\{sm8, sm13\}$
20	$\{t90, t90^-, t180\}$		

at one of the states in X_{goal} that minimizes the cost function J . On the other hand, when the robot executes Task 2, it needs to visit all states in X_{goal} , regardless of the ordering, by following a path that minimizes the cost function J . We make the following assumptions:

A1. There may exist static or mobile unpredictable obstacles in the environment, so that some transitions of the environment automaton are not allowed to fire either definitely or temporarily. If the detected obstacle is a static one, then the transition blocked by it will be blocked definitely. On the other hand, if the detected obstacle is a mobile one, possibly another robot, the transition is temporarily blocked, and thus, the robot can resume its navigation after its trajectory becomes free again.

A2. A robot does not know the position of the other robots in the environment, and it is unable to distinguish robots from other types of detectable obstacles. Thus, when a robot detects another by using its sensors, it sees that robot as an obstacle, simply.

A3. There exists an external agent, referred here to as server, that is able to communicate with all robots.

Figure 2. Problem that arises when the approach presented in Gonzalez et al. (2018) is applied to multiple robots in an environment G_e that has corridors that allow robot movements in both directions.

At first glance, the single-robot navigation architecture proposed in Gonzalez et al. (2018) can be used to control the navigation of several robots in the same environment. However, this approach may fail, as illustrated by the following example.

Example 2. Consider the same navigation environment addressed in Example 1 and shown in Figure 1. Assume that two robots R_1 and R_2 are operating in this environment, and their initial poses are states 1 and 5, respectively, as shown in Figure 2(a).

Consider that robot R_1 receives a task to go to state 5 and robot R_2 receives a task that demands it to go to state 1. According to Gonzalez et al. (2018), the planners of both robots calculate the shortest paths to their goals, and thus, both computed trajectories pass through the bottom horizontal corridor. As a consequence, the robots will meet, detect each other and stop their movements. As both robots wait for each other to move away, they both consider that the other robot is a static obstacle. Then, robots R_1 and R_2 return to states 4 and 6, respectively, and recalculate the shortest path to their goals by discarding the bottom horizontal corridor as a viable trajectory. This will repeat itself in the middle and top corridors, resulting in a feasible task being deemed as impossible. The final result can be seen in Figure 2(b). $\square$

4. A DES-BASED MULTI-ROBOT NAVIGATION ARCHITECTURE

In this section, we propose a modified version of the navigation architecture proposed in Gonzalez et al. (2018) to tackle multi-robot navigation. Such a new approach adds new features to the automaton models of the robots, in order to address possible problems that arises when two robots meet facing each other.

Notice that, a possible approach to circumvent problems that occur when two robots meet facing each other is prevent such meetings. In this regard, a possible solution would be to distribute the robot tasks in such a way that two, or more, robots do not move in the same area at the same time. This solution would require either a collective trajectory planning or a collective scheduling method. However, such a solution may be conservative in the sense that it increases the computational complexity

Figure 3. The robot movement module $G_{r_m,i}$. Dashed lines represent transitions labeled with uncontrollable events.

Table 3. Robot movement module events.

Event	Description	Controllable
Σ_e	set of environment automaton events	✓
sr	stop the robot	✓
ret	return to the last visited state	✓
go	complete the last movement	✓
rs	robot stopped	×

due to the centralized planning/scheduling, and, as larger the area reserved for a given robot, as longer may be the paths computed for the other robots.

An alternative approach is to create a method of deciding, whenever two robot meet, which robot must recalculate its trajectory and which one should wait until the path is free to resume its previously calculated path. This can be done either by a local decision made between the robots or by another agent. Since it is already assumed that there are external agents that assign tasks to the robots, we will assume that there is a server that receives obstacle detection signals from all robots together with the information of their current positions and their distances to their task goals. Thus, if two robots are in poses that imply they have met head-on, the server will identify that the robots have met each other and will ask for the robot that is further away from its goal to recalculate its path, while the other robot will be allowed to continue following the previously planned trajectory. This solution is easier in terms of adapting the architecture developed in Gonzalez et al. (2018), since we only need to change the robot automaton model, G_r , and a specification automaton, $H_{spec,3}$, of the navigation problem.

4.1 The Robot Model $G_{r,i}$

In order to construct a discrete event model for the i -th robot, the features that are important for the correct planning and execution of the navigation task are separately modeled by using automata. In this paper, we propose a robot automaton model, denoted by $G_{r,i}$, which is obtained by performing the following parallel composition:

$$G_{r,i} = G_{r_m,i} \parallel G_{r_s,i} \parallel G_{r_{tm},i}, \quad (3)$$

where $G_{r_m,i}$, $G_{r_s,i}$ and $G_{r_{tm},i}$ model the robot movement, sensing and task manager modules of the i -th robot, respectively.

• *Robot movement module.* Automaton $G_{r_m,i}$, depicted in Figure 3, models the robot movement resources. The events of $G_{r_m,i}$ are listed in Table 3. In order to navigate in a given industrial environment, the robot must be able to execute the events in Σ_e . In addition, it also requires other command events to deal with unpredictable obstacles, such as, event sr , used to stop the robot in order to prevent collisions, and events ret and go , used to return the robot to the last visited state and to complete the movement interrupted by the obstacle, respectively. Automaton

Figure 4. The robot sensing module $G_{r_s,i}$. Dashed lines represent transitions labeled with uncontrollable events.

Table 4. Robot sensing module events.

Event	Description	Controllable
rs	robot stopped	×
msr	obstacle sensor information request while the robot is moving	✓
ssr	obstacle sensor information request when the robot has stopped	✓
od_i	The i -th robot detects an obstacle and sends a message to the server with the its pose and its distance from the task objective	×
$\overline{od_i}$	message sent by the i -th robot to the server, to inform it does not detect obstacles	×

$G_{r/m,i}$ has also the uncontrollable event rs , which is due to sensor readings, and represents the transition from state M , where the robot is moving, to state S , where the robot is stopped.

Its worth noticing that the events that belong to Σ are controllable, and can be cancelled either by the supervisor or by the occurrence of a new movement command.

• **Robot sensing module.** Automaton $G_{r_s,i}$, depicted in Figure 4, models the robot sensing resources. It is assumed that the robot has wheel encoders and at least one sensing system that is able to detect obstacles, such as sonars, laser rangefinders or vision-based systems. The wheel encoders are used to determine when event rs occurs, that is, when the robot stops after finishing the last movement command. The obstacle detection sensors are used to monitor the presence of unknown obstacles that block the robot path, by means of command events msr and ssr . Command event msr is used to request the execution of a sensing routine when the robot is moving, which, then, returns event od_i , $\overline{od_i}$ or rs (active event set of state S_m). Event od_i (resp. $\overline{od_i}$) indicates that an obstacle is detected (resp. no obstacle detected), and event rs indicates that the robot stopped and, consequently, the sensor reading is no longer necessary. Command event ssr is used, when the robot is stopped, to start a sensing routine that keeps $G_{r_s,i}$ in state S_s until a msr event or no obstacle detection, represented by event $\overline{od_i}$, occurs. The complete list of events of $G_{r_s,i}$ is presented in Table 4. Notice that events msr and ssr are controllable, whereas events rs , od_i and $\overline{od_i}$ are uncontrollable.

• **Robot task manager module.** Automaton $G_{r_{tm},i}$, depicted in Figure 5, models the robot resources associated with the management of the robot task. It has four states which represent the current robot status regarding task management, as follows: (i) robot idle (I), (ii) planning the robot trajectory (P), (iii) executing the task (W), and (iv) waiting for the removal of an obstacle (B). The events of $G_{r_{tm},i}$ are listed in Table 5. Event nt_i is issued

Figure 5. The robot task manager module $G_{r_{tm},i}$. Dashed lines represent transitions labeled with uncontrollable events.

Figure 6. The proposed navigation architecture.

by an external agent requesting the execution of a new task by robot i . Command event p is used to start the path planning procedure. After that, the planner starts to execute the path planning and when it is completed, the planner sends to the robot a signal, which corresponds to the occurrence of event pe . Command event ru_i (request for unblocking the path) is a robot request to an external agent to remove the obstacle between the current robot position and the last visited state. When the external agent removes the obstacle, it issues event pf_i , meaning that the path is free. Thus, events tc_i , p and ru_i are controllable, and events nt_i , pe and pf_i are uncontrollable.

Table 5. Robot task manager module events.

Event	Description	Controllable
nt_i	the i -th robot received a new task	×
tc_i	the i -th robot reports task completion	✓
p	execute the planning	✓
pe	planning concluded	×
ru_i	the i -th requests for unblocking the last path	✓
pf_i	the last path of the i -th robot is free	×

4.2 The Navigation Process

The multi-robot navigation architecture proposed in this paper consists of several robots, where each one of them is controlled by a modular supervisory controller, as shown in Figure 6. An advantage of this structure is that it allows a decentralized implementation, where the modular supervisor is embedded in the mobile robots, whereas the planner may run in external agents, which suits very well to the design problem addressed here, since it makes easier to adapt the proposed navigation architecture to other environments. In addition, the navigation architecture has also a specific type of external agent, called server, that is able to communicate with all robots (Assumption A3). The server is responsible for solving conflicts between the robots, which are configured to send to it their obstacle detection signals, together with the information of their current positions and their distances to their task goals.

The navigation process starts when the i -th robot is available and an external agent assigns a new task to it. This assignment is modeled by the occurrence of event nt_i of automaton $G_{r_{mt,i}}$ of Figure 5. Then, robot $G_{r,i}$ generates event p (execute planning), which carries the following information: (i) the robot current state; (ii) the last task assigned to the robot and its respective set of target states X_{goal} , and; (iii) set $T_{b,i}$, which is formed with those transitions identified as blocked, being initialized as an empty set and modified by the robot when event od_i occurs in $G_{r,s,i}$, i.e., the blocked transition of G_e is added to $T_{b,i}$ when the i -th robot detects a permanent obstacle. The blocked transition is determined from the last state of G_e visited by the robot and the command event in Σ_e whose execution was interrupted by the obstacle detection.

According to the diagram depicted in Figure 6, when the planner receives event p , it runs a computer application to determine the path to be followed by the robot. Notice that the planner is composed by environment automaton G_e , and weight and cost function, w and J , defined in accordance with Equations (1) and (2), respectively.

After the planning is finished, the planner sends event pe to automaton $G_{r,i}$ to inform that the planning has been concluded. The planner also sends the string of command events that corresponds to the computed path to be used to design supervisor $S_{r_{1,i}}$; thus, a new supervisor $S_{r_{1,i}}$ is computed after each new path planning completion.

The modular supervisory control $S_{r_{1,i}} \wedge S_{r_{2,i}}$ ensures the correct navigation of the i -th robot in the presence of permanent or intermittent unpredictable obstacles, and of other robots. $S_{r_{1,i}}$ acts so as to enforce the robot to follow the path computed by the planner, whereas $S_{r_{2,i}}$ ensures that design specifications SP_1 – SP_9 (to be presented in Subsection 4.4) are achieved.

4.3 Path Planning and Conflict Solving Procedures

The path planning procedure is the same proposed in Gonzalez et al. (2018), but it is worth remarking that each robot will calculate its trajectory regardless of the presence of other robots, since the position of the other robots are unknown to it.

Although each path planning process is done separately, whenever two robots meet facing each other, the server decides which robot will have to return to the previous state and recalculate its trajectory. The criteria used to choose which robot recalculates its trajectory is a project parameter. The criterion adopted in this article is the closeness of involved robots to their goals. Namely, the robot farthest from its object will recalculate its trajectory, by considering the other robot as a static obstacle, while the other robot waits its path to be free.

Consider that two robots R_1 and R_2 operate in the same environment, and meet facing each other. Suppose that R_1 is the robot that is closer to its task goal. When both robots detect each other, they send to the server a signal warning they have encountered unknown obstacles, together with the information regarding their positions and their distances to their respective goals. Then, the server infers that an encounter between R_1 and R_2 has occurred. Since robot R_1 is closer to its goal, R_2 will receive

Figure 7. Automaton $H_{spec,1}$ used to synthesize supervisor $S_{r_{1,i}}$.

a signal telling it to recalculate its trajectory, while R_1 waits until R_2 leaves its path. The server tell R_1 when its path is free, based on the information of the last state x_{last} of G_e visited by it, and the current state of R_2 . Namely, we assume that the server has a list $\ell_{server}(x)$, for each state $x \in X_e$, that stores those states where the presence of R_2 disturb the trajectory of R_1 . Thus, the server only allows the movement of R_1 when $x_2 \notin \ell_{server}(x_1)$, where x_1 and x_2 denote the current states of R_1 and R_2 , respectively. The total cost of such a verification method is $O(\|X_e^2\|)$.

4.4 Design of Modular Supervisor $S_{r_{1,i}} \wedge S_{r_{2,i}}$

In order to design supervisors $S_{r_{1,i}}$ and $S_{r_{2,i}}$, we initially construct simple automata that capture the essence of the specifications we want to ensure by using these supervisors. We, then, combine these automata with $G_{r,i}$ using the parallel composition to obtain the system desired behavior.

Let $s = \sigma_1 \dots \sigma_i \sigma_{i+1} \dots \sigma_f \in L(G_e)$ be the last string of command events computed by the planner of the i -th robot, the design of $S_{r_{1,i}}$ is performed from string s , in the same way as proposed in Gonzalez et al. (2018). Namely, we initially define the specification automaton $H_{spec,1,i} = (X_{1,i}, \Sigma_{1,i}, f_{1,i}, \Gamma_{1,i}, x_{0,1,i}, X_{1,i})$ depicted in Figure 7. In the sequel, we compute automaton $H_{1,i} = G_{r,i} \parallel H_{spec,1,i}$ that marks the applicable language requirement $K_{1,i}$. It is worth remarking that the set of events of automaton $G_{r,i}$ is $\Sigma_r = \Sigma_e \cup \{sr, ret, go, rs, msr, ssr, od, \overline{od}, t, nt, tc, p, pe, ru, pf\}$. Thus, if $P_1 : \Sigma_r^* \rightarrow \Sigma_1^*$, we can state that:

$$K_{1,i} = P_1^{-1}[L_m(H_{spec,1,i})] \cap L_m(G_{r,i}). \quad (4)$$

It is not difficult to conclude that $K_{1,i}$ is controllable. In addition, because all states of $H_{spec,1,i}$ are marked, $K_{1,i}$ is, by construction, $L_m(G_{r,i})$ -closed. Finally, an automaton realization of a nonblocking supervisor $S_{r_{1,i}}$ such that $L_m(S_{r_{1,i}}/G_{r,i}) = K_{1,i}$ is obtained from $H_{spec,1}$ by adding self-loops labeled by the events in $\Sigma_r \setminus \Sigma_{1,i}$ to all of its states.

Let us now consider the synthesis of supervisor $S_{r_{2,i}}$, which deals, among other requirements, with static and mobile (possibly other robots) obstacles. In order to achieve the desired behavior, the following specifications are enforced:

- SP_1 The robot can perform the command events in $\Sigma_e \cup \{ret, go\}$ only after it receives a new task and the trajectory has already been planned.
- SP_2 After the execution of command event ret , which, according to specification SP_6 , will only be executed after the detection of a permanent obstacle (possibly another robot), the robot cannot perform movement commands in $\Sigma_e \cup \{go\}$ before a new trajectory is computed by the planner.
- SP_3 In order to prevent the wrong functioning of low level controllers that execute the robot movements, a

command event in $\Sigma_e \cup \{ret, go\}$ cannot be sent before the execution of the previous movement has been either completed or aborted by command sr (stop the robot).

- SP_4 In order to prevent collisions, the robot continuously checks the existence of obstacles in the trajectory, and, when an obstacle is detected, it must stop.
- SP_5 After the robot stops due to an obstacle detection, it must notify the server it detected an obstacle. The server will, then, distinguish if the obstacle is a robot or not. If the obstacle is not another robot, the robot must wait a given time to check if it moves away. If the obstacle goes away before the waiting time is over, it must send an od_i signal to the server, which will, in return, tell the robot it can resume its navigation.
- SP_6 When the server infers the robot has detected a permanent obstacle, the robot must return to the last visited state in G_e , which corresponds to the last pose visited in the environment, by using command event ret .
- SP_7 When the robot detects a permanent obstacle while it executes the movements associated with command event ret , it must request an external agent to remove this obstacle by means of event ru .
- SP_8 When the i -th robot detects another robot, and the i -th robot is farther from its task goal, then, it must return to the last visited state in G_e , which corresponds to the last pose visited in the environment, by using command event ret .
- SP_9 When the i -th robot detects another robot, but the i -th robot is closer to its task goal, then, it must wait until the detected robot moves away. After the detected robot has gone out of the sensor's range, the i -th robot must inform this to the server, which will send a t_d signal informing when the i -th robot will resume its navigation.

Specifications SP_1 – SP_4 and SP_7 have been also imposed in Gonzalez et al. (2018). On the other hand, the new specifications SP_5 , SP_6 , SP_8 and SP_9 establishes the interaction between the mobile robots and the server. We will now construct the specification automata that capture the essence of specifications SP_i , $i = 1, \dots, 9$. To this end, we first construct automaton $H_{spec,2,i}$ depicted in Figure 8, whose set of events is $\Sigma_2 = \Sigma_e \cup \{nt_i, p, pe, tc_i, ret, go\}$ and accounts for specifications SP_1 and SP_2 . In the sequel, we compute automaton $H_{spec,3,i}$, depicted in Figure 9, that accounts for specifications SP_3 – SP_9 . It is worth remarking that automaton $H_{spec,3,i}$ differs from automaton $H_{spec,3}$ computed in Gonzalez et al. (2018), since the former accounts for the new specifications SP_5 , SP_6 , SP_8 and SP_9 . The event set of $H_{spec,3,i}$ is $\Sigma_3 = \Sigma_r \setminus \{nt, pe\}$, and its states correspond to the following situations: (i) state 0 represents the case when the robot has stopped without detecting obstacles; (ii) states 1 and 2 correspond to the case when the robot is executing the movements associated with the command events in Σ_e ; and (iii) states 3 to 16 are associated with the procedure to handle obstacles.

Automaton $H_{2,i}$ that marks the applicable language requirement $K_{2,i}$ is computed by performing the parallel composition $H_2 = G_{r,i} \parallel H_{spec,2,i} \parallel H_{spec,3,i}$. Thus, by defining projections $P_2 : \Sigma_r^* \rightarrow \Sigma_2^*$ and $P_3 : \Sigma_r^* \rightarrow \Sigma_3^*$, then,

Figure 8. Automaton $H_{spec,2,i}$ used to synthesize supervisor $S_{r_{2,i}}$. Dashed lines represent transitions labeled with uncontrollable events.

Figure 9. Automaton $H_{spec,3,i}$ used to synthesize supervisor $S_{r_{2,i}}$ for the navigation of multiple robots. Dashed lines represent transitions labeled with uncontrollable events.

$$K_{2,i} = L_m(G_{r,i}) \cap P_2^{-1}[L_m(H_{spec,2,i})] \cap P_3^{-1}[L_m(H_{spec,3,i})]. \quad (5)$$

It can be checked that $K_{2,i}$ is controllable and $L_m(G_{r,i})$ -closed. In addition, An automaton realization of a non-blocking supervisor $S_{r_{2,i}}$ such that $L_m(S_{r_{2,i}}/G_{r,i}) = K_{2,i}$ is obtained by calculating the parallel composition $H_{spec,2,i} \parallel H_{spec,3,i}$. Notice that the set of events of $H_{spec,2,i} \parallel H_{spec,3,i}$ is equal to Σ_r , and, thus, we do not need to add self-loops to it in order to obtain a realization of supervisor $S_{r_{2,i}}$.

According to modular supervisory control theory presented in Section 2, the modular supervisory architecture constructed by the conjunction of $S_{r_{1,i}}$ and $S_{r_{2,i}}$ is such that $L_m(S_{r_{1,i}} \wedge S_{r_{2,i}}/G_{r,i}) = K_{1,i} \cap K_{2,i}$, where $K_{1,i}$ and $K_{2,i}$ are defined in Equations (4) and (5), respectively. In addition, it can be verified that the admissible languages $K_{1,i}$ and $K_{2,i}$ are nonconflicting, which ensures that the conjunctive modular supervisor $S_{r_{1,i}} \wedge S_{r_{2,i}}$ is nonblocking, i.e., $L(S_{r_{1,i}} \wedge S_{r_{2,i}}/G) = K_{1,i} \cap K_{2,i}$.

Example 3. Consider, again, the problem addressed in Example 2, where two robots R_1 and R_2 are operating in the hypothetical industry 4.0 environment shown in Figure 1, being controlled by the navigation architecture proposed in Section 4. The initial pose of robot R_1 (resp. robot R_2) is state 1 (rep. state 5), as shown in Figure 2(a), and its task is to go to state 5 (resp. state 1).

Initially, the planners of both robots calculate the shortest paths to their goals, and thus, both computed trajectories pass through the bottom horizontal corridor. As illustrated in Figure 10, when the robots are facing each other in that corridor, the server, then, determines that R_1 and R_2 have encountered each other, and, since R_1 is closer to its goal, it will wait for a *timeout* signal from the server for completing its task. Meanwhile, robot R_2 will, turn 180°, move to state 8, turn 180° again, and recalculate the shortest path from its current pose, state 6, to state

Figure 10. Result obtained with the proposed approach.

1, by considering that the transition from state 6 to state 2 (which accounts for the bottom horizontal corridor) is blocked. Thus, robot R_2 reaches its goal (State 1) passing through the middle horizontal corridor instead of the bottom one, whereas robot R_1 reaches its goal (State 5) passing through the bottom horizontal corridor. $\square$

5. CONCLUDING REMARKS

In this paper, we extend the single-robot DES-based navigation architecture previously proposed in Gonzalez et al. (2018), to deal with the navigation of multiple mobile robots. We consider several robots navigating independently of each other, in an Industry 4.0 environment where there may exist static and dynamic obstacles, that are *a priori* unknown by the robots. Simulated experiments illustrate, in a hypothetical Industry 4.0 environment, that the single robot navigation architecture presented in Gonzalez et al. (2018) was extended by incurring little extra computational effort, since each robot computes its path independently. The modular design proposed in this paper provides an approach that scales better than that presented in Tatsumoto et al. (2018), since the computational cost of their approach grows exponentially with the number of robots. On the other hand, Hill and Lafortune (2017) did not provide a computational complexity analysis, however, its multi-level hierarchical architecture requires complex procedures to obtain abstractions of the supervisors. Moreover, none of the approaches proposed in Dulce-Galindo et al. (2019); Hill and Lafortune (2017); Tatsumoto et al. (2018) and Basile et al. (2019) is able to deal with unknown obstacles.

It is worth remarking that, although the achieved overall computational cost does not increase significantly with the number of robots, our approach can cause unwanted robot encounters, that demands additional computation to be solved. This drawback shall be tackled in future works. Another possible future work is include the distribution of the tasks for the robots (Dulce-Galindo et al., 2019; Basile et al., 2019).

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