An Institutional Robotics Approach to the Design of Socially Aware Multi-Robot Behaviors

Alicja Wasik, Alcherio Martinoli and Pedro U. Lima

Abstract— **We propose an institutional robotics approach to the design of socially-aware multi-robot systems, where cooperation among the robots and their social interactions with humans are guided using institutions. Inspired by the concepts stemming from economical sciences, robot institutions serve as coordination artifacts, which specify behavioral rules that are acceptable or desirable given the situation and which can be replaced by other rules to enforce new acceptable or desirable behaviors without changing the robot's core code. In this paper we propose a formal methodology for consistent design of coordinated multi-robot behaviors intended for use in human-populated environments. We illustrate theoretical concepts with practical examples. Graph-based formations serve as a basis for coordinated multi-robot behaviors and concepts from the literature on human-aware navigation provide social rules that are enforced by the institutions. Experiments are carried out in a high-fidelity robotic simulator to illustrate the application of the theoretical concepts.**

I. INTRODUCTION

Multi-robot cooperative behaviors are becoming increasingly pervasive in real-world applications. To be socially aware, robots should use social norms devised by humans, which can differ from culture to culture. Existing methods allow for successful cooperation of multiple robots, but the human factor is often ignored or the person is treated as a moving obstacle. On the other hand, although human-aware navigation is a widely studied subject, only few studies discuss multiple robots behaving cooperatively in human-populated environments. Most works focus on human guidance, where strategies stem from early research on flocking herds [1], treat the group of humans as a particle [2] or assume that humans simply follow the robot [3]. Such solutions are largely oversimplistic. More realistic studies [4] ensure that the robots respect personal space of the humans. The state of research in human-aware navigation is largely mature in the single robot case. But when it comes to studies of cooperative multi-robot systems, the presence of a person is handled inappropriately or even naively, solutions are heuristic or difficult to generalize. Our intention is to provide a mechanism for abstraction of the underlying methods and to systematize and unify development of social-aware, multi-robot behaviors using the concept of institutions.

The goal of Institutional Robotics (IR) [5] is to provide a strategy for specifying complex social interactions. Drawing inspiration from institutional economics, IR has been proposed with the aim to address the need for presence of coordination devices in multi-robot systems and to facilitate integration of robots in human societies. Since the robots controlled using the IR approach abide by the norms of institutional environments created by the humans, the collective performance during human-robot interaction is expected to surpass the existing methods. In the field of multi-robot systems, institutions have been introduced [5], formalized [6], used for modelling and implementation [7] of simple robotic behaviors. They also raised some interest in the social robotics community [8]. In [5] institutions are defined as artificial modifications that influence the collective order. Robot institutions are formally represented in [6] using Petri nets, which encapsulate the behavioral rules to execute a desired task and observe the specified social interactions. Validated in [6] in simulation and in [7] in real-world implementation, the institutional controller coordinates a swarm of 40 robots to maintain wireless connectivity. The predominant reason behind IR was to exceed the collective performance during human-robot cooperation. To the best of our knowledge, however, up to now IR has not been exploited to introduce the social aspect in multi-robot systems.

We propose a new methodology for development of socially aware multi-robot behaviors based on the IR framework. The new formalism allows us to deal with both high-level behavior management, such as decision making and planning, and low-level reactive coordination, such as formation control. Institutions introduce social rules inspired by human institutions that guide cooperation between the robots and result in mutual understanding between the robots and the humans. We focus on transparency and generality of the formalism, where its abstract representation allows for the use of miscellaneous robot behaviors and integration of social constraints of diverse nature. To illustrate the theoretical concepts, we apply the formalism to our work on robot formations [9], where we govern a graph-based formation behavior using one of the institutions. Proxemics [10] and social forces [11] form a set of social constraints that change the formation parameters (geometry, roles, trajectories). For realization of the robotic controller we use Petri Nets (PN).

This paper is organized as follows. Section II lists the aspects of social robot behaviors. The role of institutions in shaping such behaviors is described in Section III. An example of application is given in Section IV and the case studies are given in Section V. We draw conclusions in Section VI.

Supported by ISR/LARSyS Strategic Funds from FCT project FCT[UID/EEA/5009/2013] and FCT/11145/12/12/2014/S PhD grant.

Alicja Wasik and Pedro Lima are with the Institute for Systems and Robotics, Instituto Superior Técnico, Universidade de Lisboa, Portugal. `alicja.wasik@epfl.ch` and `pal@isr.ist.utl.pt`

Alicja Wasik and Alcherio Martinoli are with the Distributed Intelligent Systems and Algorithms Laboratory, School of Architecture, Civil and Environmental Engineering, École Polytechnique Fédérale de Lausanne, Switzerland. `alcherio.martinoli@epfl.ch`

II. SOCIAL ROBOT BEHAVIORS

Consider a team of mobile robots deployed in environments populated with humans, such as museums or airports. The robots occasionally are required to perform a cooperative task without interrupting human activities and taking into account social rules. For instance, robots may be requested to guide a group of people, control the movement of the crowd, or temporarily block a passage. In order to do so in a socially aware manner, the robots need a basic understanding of the principles that govern human environments.

A. Behaviors and Actions

The tasks and functionalities that the robots may be required to perform are called *behaviors*, B. For the robot formation, the behaviors may include patrolling or human guidance. Behaviors are composed of basic building blocks - *actions*. *Individual actions* A_O do not involve social interaction, neither between the robots, nor between robots and humans. Actions that entail social interaction are *social actions* A_S. A set of all possible actions is $A = \{A_O \cup A_S\}$. B provides an ordering for the actions, it assures that the actions are executed in the correct order, sequentially or concurrently. More formally, $B_i \in B = (V, E)$ is a graph with the nodes V being the actions in A, $V : \{a \in A\}$.

B. Rules, Roles and Knowledge

When in a social situation, robots have to comply with the *rules* that govern human environments. Such rules include respecting personal space, giving a way at the door or passing on a right hand side of a corridor. The set of rules is an essential element directing behavior of the robots, rules directly encode social constraints and define what robot should and should not do. Rules R are operators on the set of actions that have the power to allow, forbid, select or modify the actions

Since the rules can allow and forbid actions, they decide what *roles* the robots can assume. When a robot plays a role, it is obliged to perform a set of actions assigned to this role and forbidden to take actions that are not permitted. Rules of the formation could allow the robot to take the role of a leader or a follower, or specify its decision making powers.

In order for the robot to comply with the rules, it must have *knowledge* about how to act according to the them. Types of information contained in the knowledge can range from parameters and data structures to complex algorithms. Stating that the rules can modify the actions means that the rules can change the parameters of the action, encoded by the knowledge. Knowledge K provides a common grounding for the robots, for the rules and actions to be based upon the same type of information. Common knowledge implies that every participant knows how to act, and knows that the others know how to act [12]. For the robots to navigate in a formation, they must know, among many others, each other's positions in the environment, what roles are assigned to whom and what it means to change formation shape from line to square. More importantly, the knowledge provides recipes for socially adequate interactions with humans. Thus, the knowledge incorporates the facts, beliefs and temporal information, as long as this information is imperative for the cooperation and interaction.

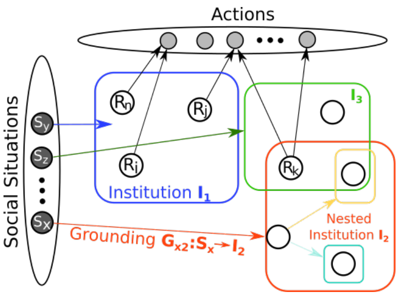

Fig. 1: Social situations activate the corresponding institutions, which, by evoking their rules, operate on the robot actions.

III. ROLE OF THE INSTITUTIONS

Common knowledge, common rules and roles known by all the robots are the pivotal concepts giving rise to socially aware behaviors. They reduce uncertainty, facilitate decision-making and promote cooperation, so that the cost of coordinating and other activities can be lowered [13]. They are the core of what is known in human environments as ***institutions***. An institution can be regarded as a set of rules governing social interactions [14]. By sharing the institutional environment, the robots attain a good approximation of the situation and expectation that the others follow the same prescriptions enforced by the institutional rules.

A. Institutional Grounding

It has been said that the rules and the knowledge are the central parts of the institutions. Indeed, institutions encapsulate knowledge and the rules that correspond to a state of the environment and the participants (humans and robots) when a social interaction takes place. Such state is called a *social situation* S (action situation in [14]). An institution I is active during a specific social situation it has been designed for. Since one social situation may occur in different parts of the environment, involve various participants and have other dissimilar conditions, the robots must be able to recognize it. The process of recognition of a social situation and activation of the corresponding institution is called the *grounding*, $G : S \to I$. When a robot activates the institution, it becomes its *actor* and is obliged to act according to its rules. The institutional rules constrain robot actions differently depending on the social situations, robots do not need to reason about the rules and do not need to be reprogrammed every time they join a new instance of social situation.

B. Institutional Rules

A set of rules of institution I is an operator on a set of actions:

$$R_I : 2^{A_S} \to 2^{A_S} \tag{1}$$

The institutional rules map the social actions A_S according to a social situation, for which that institution is active (see Fig. 1). The rules of active institution can evoke, modify, or constrain the actions. Thus, when in a social situation, the robots engage in an *institutional behavior* B_I composed of nodes $A_I \subseteq A_S$ from a subset of social actions $V : \{a \in A_I\}$.

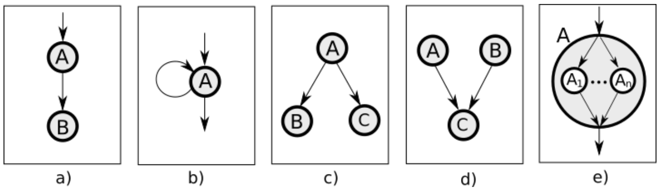

Fig. 2: Types of relations between the nodes of the RG.

As an example, consider a social situation when the robots are requested to guide a group of people. The robots are to approach the group, $a_{approach}$, inform humans that they will be lead to a new location, a_{speak}, and move together with them, a_{guide}. Thus, the institutional rules would compose three actions, $a_{approach}$! a_{speak} ! a_{guide} sequentially.

C. Networks of Institutions

An *institutional environment* of the robot is composed of one or more institutions. A robot can can be an actor of multiple institutions, it joins an institution upon recognition of a social situation and leaves an institution when the situation concludes. Activation of one institution can be a natural consequence of termination of another. Multiple institutions can be active simultaneously as long as the functioning of one institution does not interfere with the functioning of another. The order of the institutional environment is assured by defining how the institutions are allowed to interact. For this purpose, we propose *relational graphs*.

Definition 1. *Relational graph* (RG) is a directed graph defining the relationship between institutions present in the institutional environment of the robot. A node of the graph encapsulates the institutional behavior, B_i 2 B_I, or an individual behavior B_j 2 B_O. The edge linking two nodes defines the relation between them.

The relational graph is composed of the institutional behaviors B_I (which in turn are composed of social actions in A_S) and of the individual behaviors (composed of individual actions in A_O). The RG regulates which institutions can be active at a given time and assures that the actions of conflicting institutions do not run concurrently. Institutions can be *nested*, meaning one general institution can consist of several specialized institutions. According to its rules, the general institution can evoke one or a subset the nested institutions (see Fig. 1).

The RG is a mathematical behavior model used for forming dependencies between complex behaviors composed of multiple actions. As such, it can be readily used as the robot controller. The abstract definition of the RG allows for the use of a wide range of mathematical tools for building its representation. Most of the graphical modeling languages, including finite state automata, behavior trees, Petri nets and variations thereof are suitable for that purpose. Although the exact definition of the relations within RG depends on the choice of the modeling language, we provide an intuitive guide to building the network of institutions.

1) Roles of the RG nodes: Each node of the RG encapsulating the behaviors in B provides a high level compact representation of more complex compositions of actions. A node is said to be active when at least one of the actions it contains is executing. Execution of the node can be instantaneous, continue for a finite amount of time or continue until it is ceased by an internal or an external event (similarly as an institution can be activated or terminated due to the social situation). Upon completion of the execution, the node triggers execution of its direct successors. After that it becomes inactive. The RG can be static or dynamic. Since, by the definition, the institutions are activated when the robot recognizes a social situation, it means that the robot must always perform an action of recognizing social situations. The outcome of this action triggers activation of the relevant institution (activates the B_I of that institution).

2) Relations between the RG nodes: Fig. 2 shows types of relations between the nodes of the RG. Fig. 2a) is a sequence. Fig. 2b) is a self-loop, where after being activated once, A is always active. Fig. 2c) is simultaneous execution. Note that B and C should not include actions that have a potential to interfere with each other. Node C in Fig. 2d) can only be activated after its predecessors (nodes A and B) have concluded their execution. Finally, node A in Fig. 2e) illustrates a nested institution, where internal rules of the general institution evoke a subset of specialized institutions. When A is activated, a subset of A_1 to A_n becomes active.

D. Creation, Evolution and Monitoring of Institutions

A human institution is a product of deliberate design or it arises spontaneously [13]. The creation of a robot institution is dictated by the presence of a social situation, while the desired outcome of using that institution is its *rationale*.

According to [15], rules of human institutions without obligatory sanctions are useless. Such rules are always monitored and enforced. Robots, as artificial agents, are not motivated to break rules, nor do they reveal opportunistic behaviors. However, sanctions and rewards given to the robots can help to regulate and monitor institutional environments, identify conflicting rules and inconsistencies. The sanctions and rewards for respecting or breaking institutional rules are the *payoffs* of the institution: P_I = f($sanction, reward$) 8 r_i 2 R_Ig.

Robot institutions can be modified by cooperative decision making, or by an individual with a power to do so. Experience gained by the robots participating in a social situation can lead to gradual modification of the existing rules. For this to happen, the performance becomes a part of the institution and is stored in the *memory* of that institution: M_I = f($pm_1, ..., pm_n$) 8 B_i 2 B_Ig, where $(pm_1, ..., pm_n)$ is a set of relevant performance measures. In this way, the robots jointly contribute to evolution of the institution. More importantly, the rules remain consistent among the participants and retain the power to reduce the cost of coordination [14].

E. Institutional Formalism

The definition of institution is object of discussion among the economists, where the interpretation of institution, organization and rule is done according to the purpose they serve [16]. Similarly, the fields of IR, normative multi-agent systems [17] and computational organization theory [18] operate on diverse definitions. Even within the field of IR, institutions are modeled dissimilarly among different research groups. Nevertheless, the core concepts, based on the economic theory, remain the same.

The definition of a robot institution we propose in this paper is not intended to be a general, one-size-fits-all solution. Indeed, we believe that similarly as in the social studies, robot institutions should serve their core purpose - of guiding social interactions.

Definition 2. *Institution* is a tuple

$$\langle \textit{ID, Actors } T_I, \textit{ Knowledge } K_I, \textit{ Rules } R_I, \textit{ Behavior } B_I, \textit{ Actions } A_I, \textit{ Memory } M_I, \textit{ Payoff } P_I \rangle$$

This definition stems from political economy studies [12] conducted by Elinor Ostrom, winner of the Nobel Prize in Economics in 2009:

> *"Institutions can be defined as the sets of working rules that are used to determine* ***who is eligible to make decisions*** *in some arena,* ***what actions are allowed or constrained, what aggregation rules*** *will be used,* ***what procedures*** *must be followed,* ***what information*** *must or must not be provided, and* ***what payoffs*** *will be assigned to individuals dependent on their actions."*

In summary, *ID* is a unique identifier of the institution, composed of its *Name* and a *Rationale*, which states what the desired outcome of the institution is (why the institution is useful). *Actors* defines which robots are allowed to activate the institution, *Institutional Behavior* provides the ordering for the actions, while *Social Actions* are the recipes for performing the social actions, *Knowledge* describes what information the robot must possess in order for it to act, *Rules* allow, constrain or modify the actions, *Memory* retains robot experience. *Payoffs* are the rewards and sanctions for conforming or breaching the rules.

IV. Application of the Methodology: Institutional Network for Formation Behaviors

As a proof of concept, we apply the proposed formalism to our existing work on reconfigurable multi-robot formations [9]. The existence of socially adequate cooperative behavior relies on a few essential aspects that can be categorized as social situations. 1) *Situational awareness*. Robots are able to localize themselves in the known map, detect obstacles and distinguish humans. To establish a formation, robots need to know each other's positions. 2) *Formation control*. Robots running the same formation control algorithm are capable of changing the formation shape and its connectivity. They avoid obstacles as a unit or individually. 3) *Human-robot interactions*. Robots are aware of the social constraints present in human environments and modify their behaviors in order to respect them. 4) *Global group objective*. A *virtual leader* (VL), provides the group objective, a trajectory, and communicates to the robots its virtual position. VL is perceived by all the robots as one of the team members and included in the formation algorithm as if it were a real robot.

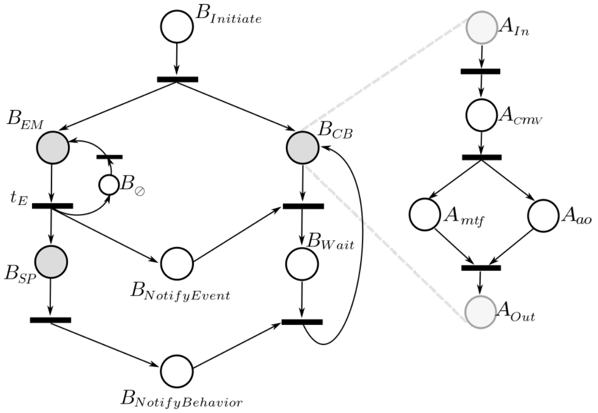

Fig. 3: The PN-based representation of the RG.

We assume that the robots perform a default formation behavior, until the robots receive a task that involves interaction with humans, thus indicating a new social situation. Note that while moving in a formation, the robots interact with each other, so they are already situated in one social situation.

A. Institutions for Formation Behaviors

Given the above classification, the institutional network is comprised of four institutions:

1) Environment Monitoring I_{EM}: The I_{EM} assures that all the robots have means to build consistent world models. The actors of I_{EM} localize on the known map, communicate with the other robots and the virtual leader to obtain their positions and monitor for social situations. Upon recognition of a social situation, successor nodes of I_{EM} are activated.

2) Collective Behaviors I_{CB}: The I_{CB} offers the robots a common basis for understanding the specification of the formation behavior. By knowing and following the rules R_{CB}, each robot knows its role in the formation, the roles of the other robots and parameters of the formation, including shape, distances and connectivity.

3) Social Planning I_{SP}: I_{SP} is responsible for devising a social plan for guiding interactions with the humans. Only one actor can be active at any given time and we assume that the robot that recognizes the social situation first, activates I_{SP}. I_{SP} is a nested institution, it delegates control to specialized institutions. In our case studies, we will consider two specialized institutions, I_{SP}^{Bl} for a *blocking* task, and I_{SP}^{Acc} for *accompanying* task. Knowledge of I_{SP} comprises of methods from the human-aware navigation literature, such as proxemics and social forces. According to the rules, the actor plans the behavior of the group, including the shape and path of the formation, so as to respect social constraints.

4) Virtual Leader I_{VL}: I_{VL} is run by one dedicated actor. I_{VL} involves a set of planning actions, responsible for interpretation of the task and planing the path, and execution actions, which simulate movement of the VL and broadcast its pose. Since the VL is perceived as one of the formation members, it guides the formation to achieve its objectives.

B. Relational Graph for Formation Behaviors

We use a Petri net-based representation of the RG. PNs are sufficiently general to model behaviors of extremely varying types, such as parallelism, concurrency and synchronization,

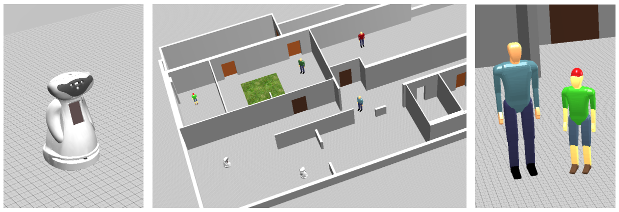

Fig. 4: The Webots simulator (Middle), the MBot robot (Left) and simulated models of child and adult (Right).

while providing a high degree of modularity. A gentle introduction to PNs can be found in [19]. The PN-based representation of the RG used for coordination of socially aware multi-robot behaviors is shown in Fig. 3.

The RG is composed of three nodes that represent institutional behaviors. B_{EM} that gathers information about current situation and B_{CB} that controls the formation are active by default. When one of the robots recognizes a social situation (passing control from B_{EM} to B_{SP} and $\mathrm{B}_{NotifyEvent}$), it notifies all the team members to temporarily halt execution of the current behavior (deactivating B_{CB} and activating B_{Wait}). B_{SP} plans the new formation parameters according to R_{SP} and passes them to all the other robots in $\mathrm{B}_{NotifyBehavior}$. The outcome of B_{SP} updates the knowledge of the I_{CB}, setting new formation parameters and the knowledge of I_{VL}, specifying a new task. Upon receiving the new parameters, the robots preempt B_{Wait} and resume formation in B_{CB}. Due to lack of space, we only show structure of one institutional behavior, B_{CB}. In B_{CB} the robot computes the motion vector in A_{CMV}, then it moves towards the desired place in the formation in A_{MTF}, while simultaneously avoiding the obstacles in A_{AO}.

V. CASE STUDIES

The aim of the case studies is to show diversity of the behaviors that the robots can engage in under the network of institutions. We illustrate two social situations, where interactions with humans are of two different sorts: in case A robots modify behavior of a person, in case B they adhere to the social conventions. The default behavior is formation patrolling and the RG graph serves as the robot controller. Experiments are performed in realistic simulator Webots [20] (Fig. 4), with holonomic MBot robots [21] developed within the FP7 European project MOnarCH (Multi Robot Cognitive Systems Operating in Hospitals) with the goal of introducing social robots in the pedriatric wing of a hospital[1]. The robots are equipped with navigation, perception and low-level safety sensors, accurately simulated and calibrated using real data. Robots self-localize using AMCL[2] from ROS.

A. Case Study I: Blocking

In the "*blocking*" task the robots influence behavior of the humans by blocking a specific passage. To execute the task, a minimum number of robots required to block the passage moves towards the designated space and assumes blocking positions. Upon receiving the "*blocking*" task, one of the robots becomes an actor of I_{SP}^{Bl}, a nested institution of I_{SP}. Knowledge of I_{SP}^{Bl} uses *social forces* model for predicting the behavior of the person when encountering a number of robots in the passage. Social forces reflect the psychological motivation behind the pedestrian behavior, they represent the influences of the environment and of the other pedestrians on the human motion [11]. There are two fundamental rules in R_{SP}^{Bl}: *"Dispatch the minimal number of robots"* and *"Establish optimal blocking configuration"*. According to R_{SP}^{Bl}, the actor of I_{SP}^{Bl} finds a minimal repulsive force, required to drive a person back from the area and the number of robots N_B and their configuration needed to generate that force. Furthermore, R_{SP}^{Bl} specify how to assign, which N_B robots engage in the blocking behavior, and which robots remain patrolling. The formation splits into two groups, and the virtual leader provides two trajectories, one for patrolling and one leading to the passage to be blocked.

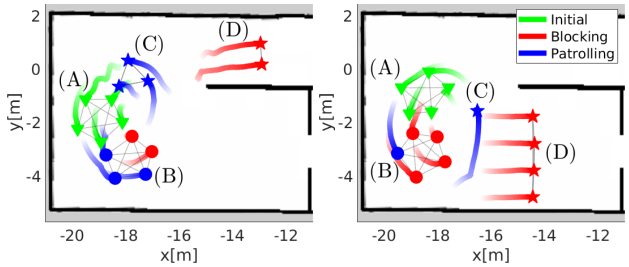

Fig. 5: Case Study I. Trajectories of the robots blocking narrow (upper) corridor and wide (lower) corridor.

1) Results: We performed two experiments with varied width areas to be blocked, (i) narrow and (ii) wide, each of five runs. In all experiments, five robots are patrolling in a pentagon-shaped formation, upon receiving a task, split into two formations with (i) $N_B = 2$ and (ii) $N_B = 4$. Trajectories of the robots are shown in Fig. 5, with the initial patrolling behavior (A), assignment of the robots upon splitting (B) and two formations performing patrolling (C) and blocking (D).

B. Case Study II: Accompanying

In the "*accompany*" task, the robots "accompany" a person that passes through part of the environment, at the same time respecting human comfort. Social norms, encoded in the knowledge of I_{SP}^{Acc}, are based on *proxemics*, a study of spatial separation that people naturally maintain between themselves and the others [10]. Proxemics serve to constraint motion of the robots by providing a minimal distance the robot should keep from a person. The associated rules R_{SP}^{Acc} state *"Maintain a formation with the person"* and *"Do not enter personal space"*, where personal space is a circle around the human, with the diameter depending on his age, gender and personality. The virtual leader guides the formation to the person and then, by imitating position of the human, seamlessly allows for including the human in the formation. R_{SP}^{Acc} specify the shape of the formation and the human-robot distances, proportional to size of the personal space.

1) Results: The accompanying behavior is illustrated in Fig. 6. Two robots wait until a person, child or an adult, enters the door (A), keep a triangle formation with the

---

[1] MOnarCH, FP7, FP7-ICT-2011-9-601033 (http://monarch-fp7.eu)

[2] AMCL (http://wiki.ros.org/amcl)

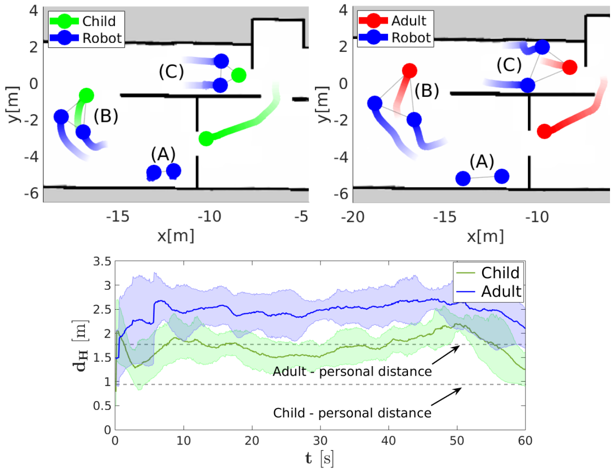

Fig. 6: Case Study II. (Top) Trajectories of the robots and the person. (Bottom) Average distances between the robots and the human.

human (B), and follow until the exit (C). In this example, the personal space of the child is $d_P^{child} = 0.94m$ and of the adult is $d_P^{adult} = 1.77m$. Fig. 6 (Bottom) shows the mean distances d_H between the robots and the human averaged over 5 runs. Since d_H is always above d_P^{child} for the child and d_P^{adult} for the adult, robots respect social space of the person by converging to a formation of appropriate size. The simple rules of I_{SP}^{Acc} allow for variability (parametrization) of the behavior according to the social context.

C. Discussion

The two presented case studies illustrated the degree of variability associated with multi-robot behaviors situated in a social context. The institutional approach allowed for incorporation of the social rules, often of inconsistent nature (such as proxemics or the social forces), in a unified methodology. Moreover, variability of the social norms existing among the individuals and among the cultures was reflected by adequate parametrization of the institutional rules. The proposed case studies illustrated only simple instances of social situations. How the robots recognize social situations and what perception capabilities are required are the topics of future work.

VI. CONCLUSIONS

In this paper, we proposed an institutional robotics approach to the design of socially-aware multi-robot systems, where cooperation among the robots and their social interactions with humans are guided by institutions. We introduced a formal methodology for the design of complex multi-robot behaviors conforming to social rules that govern human societies. A network of institutions provided means to impose social constraints on the robot behavior in a unified methodology. Formal definition of the institutions allowed for unambiguous specification of their purpose, responsibility, and consequences, as well as identification of the relational ties present in the institutional environments. As a proof of concept, we applied the formalism to our previous work on multi-robot formations. We presented a complete system composed of four institutions and defined the associations among them. In two case studies we illustrated the diversity of the behaviors the robots can engage in under the network of institutions. By requiring the robots to engage with humans, we have shown that the institutions can govern social interactions according to well known methods, without the need to resort to case-specific heuristic solutions.

In the future work, we intend to gain further insight in the organization of human institutions to further improve the proposed concepts. We plan to evaluate our approach in more complex scenarios with multiple humans and perform test with real robots. As a vital part of our study, we will allow for modification of the institutional environment by the robots, investigating the idea of institutional evolution and learning.

REFERENCES

[1] M. A. Potter, L. Meeden, and A. C. Schultz, "Heterogeneity in the coevolved behaviors of mobile robots: The emergence of specialists," in *Proc. of the 17th Int. Joint Conf. on Artificial Intelligence (IJCAI)*.
[2] E. A. Martinez-Garcia, A. Ohya, and S. Yuta, "A multi-robot system architecture for trajectory control of groups of people," *Cutting Edge Robotics*, pp. 449–466, 2005.
[3] S. Zhang and Y. Guo, "Distributed multi-robot evacuation incorporating human behavior," in *Asian Journal of Control*, vol. 17, pp. 34–44, 2015.
[4] A. Garrell and A. Sanfeliu, "Cooperative social robots to accompany groups of people," *The Int. Journal of Robotics Research*, vol. 31, no. 13, pp. 1675–1701, 2012.
[5] P. Silva and P. U. Lima, *Institutional Robotics*, pp. 595–604. Springer Berlin Heidelberg, 2007.
[6] J. N. Pereira, P. Silva, P. U. Lima, and A. Martinoli, "Formalization, Implementation, and Modeling of Institutional Controllers for Distributed Robotic Systems," *Artificial Life*, vol. 20, no. 1, pp. 127–141, 2013.
[7] J. N. Pereira, P. Silva, P. U. Lima, and A. Martinoli, "An experimental study in wireless connectivity maintenance using up to 40 robots coordinated by an institutional robotics approach," in *IEEE Int. Conf. on Intelligent Robots and Systems*, pp. 5073–5079, 2013.
[8] S. Tomic, F. Pecora, and A. Saffiotti, "Too cool for school - adding social constraints in human aware planning," in *Proc. of the 9th Int. Workshop on Cognitive Robotics, CogRob (ECAI-2014)*, 2014.
[9] A. Wasik, J. N. Pereira, R. Ventura, P. U. Lima, and A. Martinoli, "Graph-based distributed control for adaptive multi-robot patrolling using local formation transformation," in *IEEE Int. Conf. on Intelligent Robots and Systems*, pp. 1721–1728, 2016.
[10] E. T. Hall, *The hidden dimension*. Doubleday & Co, 1966.
[11] D. Helbing and P. Molnár, "Social force model for pedestrian dynamics," *Physical Review E*, vol. 51, no. 5, pp. 4282–4286, 1995.
[12] E. Ostrom, *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge University Press, 1990.
[13] E. G. Furubotn and R. Richter, *Institutions and Economic Theory: The Contribution of the New Institutional Economics*. University of Michigan Press, 2005.
[14] E. Ostrom, *Understanding Institutional Diversity*. Princeton University Press, 2005.
[15] W. Kasper and M. E. Streit, *Institutional Economics*. No. 1582 in Books, Edward Elgar Publishing, July 1999.
[16] G. M. Hodgson, "What are institutions?," *Journal of Economic Issues*, vol. 40, no. 1, pp. 1–25, 2006.
[17] C. Hollander and A. Wu, "The Current State of Normative Agent-Based Systems," *Journal of Artificial Societies and Social Simulation*, vol. 14, no. 2, p. 6, 2011.
[18] K. M. Carley and L. Gasser, "Multiagent systems," ch. Computational Organization Theory, pp. 299–330, MIT Press, 1999.
[19] R. David and H. Alla, *Discrete, continuous, and hybrid Petri nets*. Springer Science & Business Media, 2005.
[20] O. Michel, "Webotstm: Professional mobile robot simulation," *Int. Journal of Advanced Robotic Systems*, 2004.
[21] J. Messias, R. Ventura, P. Lima, J. Sequeira, P. Alvito, C. Marques, and P. Carrio, "A robotic platform for edutainment activities in a pediatric hospital," in *IEEE Int. Conf. on Autonomous Robot Systems and Competitions (ICARSC)*, pp. 193–198, 2014.