Crowding and Guiding Groups of Humans by Teams of Mobile Robots*

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***Abstract*— This article introduces a general description of a multi-robot system (MRS) architecture aimed to provide guidance for a group of humans. At a first approach, only the strategy and architecture framework are described, further than the ethological and human factors involved in human-robot interaction. The paper encompasses a special strategy to conduct and crowd multiple people. Such strategy includes a methodology to localize multi-human; a MRS architecture design; and a control for people trajectory and a robots motion planner. A key-problem in the implementation of the system is that, there is no signal of any type for accomplishing guidance. In addition, some experimental and simulation results are presented, which exhibits the effectiveness of the proposed architecture, and the social force model adapted in a manner to simulate behavior of groups of people.**

***Index Terms*— Guiding-tours, multi-robot systems, trajectory control, motion planning, guiding simulation**

I. INTRODUCTION

A first approach and attempt of a model to flock and conduct a group of humans towards a target destination by a team of mobile robots is the key-issue discussed in this paper. Studies on MRS architectures from different classification types and taxonomies has been proposed by other authors [1]-[3]. In the present context, the authors have proposed an MRS architecture with features for human-guiding and seen from a task-oriented approach. The present system can be seen as guiding-tours, nevertheless further than such concept this implementation may be though as the model given by several dogs flocking herds of sheep, guiding them toward a target place. Dogs and sheep have a minimal way of explicit communication. Sheep follow the dogs, while dogs do bark and/or approach them if there is any situation affecting the conducting process. However, in the proposed system does not exist any type of explicit signal for guidance, and trajectory control is given by an implicit way based on natural reactions of angle-velocity motions between humans and robots (see Fig.1). Besides, the authors are conscious of the human motion model considered as well as the real human behaviors which greatly differ from behavioral patterns of animals in their natural environments. The process of multi-people conduction has been defined in the present context as: moving from one point to a target location by employing certain conduction tasks, which essentially involve a mechanism to crowd people. It can be classified in three main components: (a) Guiding or conducting; (b) grouping or crowding; and (c) intercepting.

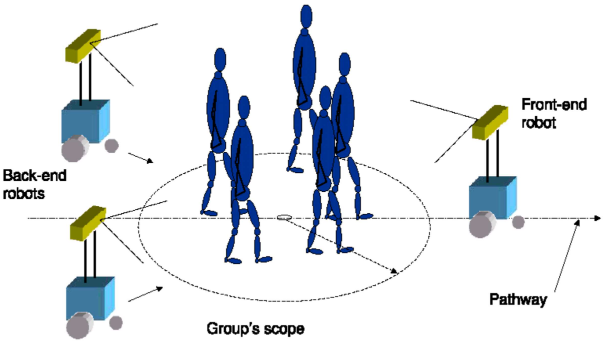

Fig. 1. Concept of multi-people guidance by a team of robots.

1) Guiding is defined as the conduction of the group of people through the pathway, people easily follows the leader robot.
2) Grouping is the process of collecting the group together still closer than it actually is, while the group is being guided. Perhaps, an undesirable situation is when the size of the group area increases overtime, such that becomes bigger than a desired size.
3) Intercepting is the situation when any person intents to leave the group, or moving away from its scope. Thus a given robot (R_b or R_c) approximates to he/she attempting to yield the person going back into the group's scope.

The present endeavor has been to research on a methodology for guiding humans by deploying multiple mobile robots and its architectural framework. Nevertheless, the task for intercepting people is out of scope of this paper as it has to deal with different kinds of problems that imply higher level complexity tasks.

Recent progress in robotics and artificial intelligence has made possible to build interactive mobile robots that operate highly reliably in crowded environments. There exist in the research field community several works concerned with guiding-tours, nevertheless tackling different problems

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and deploying different architectures. Minerva [4] and [5]; Virgil [6]; Tourbot [7]-[9]; MOBSY [10]; and SAGE [11].

II. AIM OF STUDY

The principles of people trajectory control given in the results of this research can be applicable as a general base to more complex robotic systems used in almost any situation that could imply guidance. Such as mobile robots providing aid guiding refugees in case of war or disasters toward safe places, here implicit communication and quickness are essential. Other case of application could be the one in companies guiding-tours for groups of visitors; or even in a near future a similar kind of model for guiding control may be applied for controlling herds or flocks of animals guided by mobile robots. Let us highlight that the previously mentioned cases of application must include a further study on ethology humans and/or animals in their different environments. From a technical and engineering approach this research can roughly be divided in 4 general parts to know: (a) A methodology of how a team of mobile robots can cooperatively identify and localize people in a group; (b) the design of a multi-robot system architecture (c) the way the team of robots must track multi-people while robots in motion; (d) a team-based robots motion and a guiding control was also implemented, which the group's center of gravity is the key-issue to yield steering on a desired pathway.

III. STRATEGY FOR CONDUCTION

A general strategy and considerations for accomplishing conduction is roughly divided in the following 3 points:

1) People localization (humans tracking).
2) Multi-robot architecture design.
3) Trajectory control of people and robots motion planning.
    a) Ra is the leader.
    b) Robots surround the group.
    c) Robots team in keeping-formation.

The general methodology is that a robot at front-end shows the correct path toward the goal destination while a couple of robots at the group's back, escort them to share sensory observations, as well as they contribute for controlling the group size and trajectory by affecting the speed, direction and scope of the group as showed in Fig.2.

The environment is basically compounded by indoors such as hallways and rooms. About 5 persons in two lines can easily walk in such corridors (University of Tsukuba).

IV. MULTI-ROBOT SYSTEM ARCHITECTURE

A. Robotic platform

A team of 3 self-contained robotic platforms (called Yamabico) was deployed (Fig.3). Each robot has been equipped with commercially available stereo vision sensors that provide disparity maps (sum of absolute differences), gray scale images (160x120 pixels) in real-time (noting that other sensors could be deployed). Stereo images provide a ranged model (3D) of the world in real-time. There is a central host as part of the proposed architecture that is featured by a standard PC (Pentium-4). Each robot has on-board a PC-laptop (Pentium-III) with wireless technology running under Linux. The communication is based via IEEE802.11b wireless (11Mbit/s).

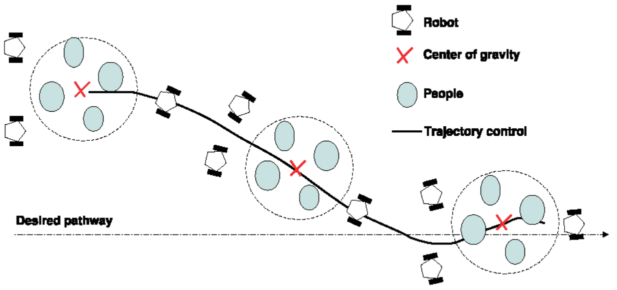

Fig. 2. Process of trajectory control carried out by a team of three mobile robots.

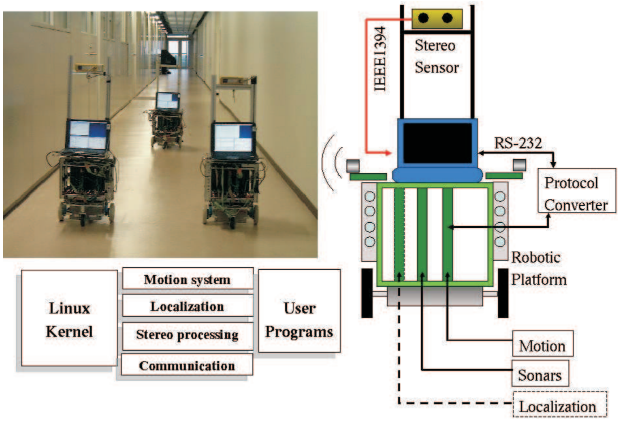

Fig. 3. Configuration of the self-contained robotic platforms.

The team of robots has also been instrumented with ultrasonic range finders. The reason was to performing a special algorithm for the robots localization that requires sensory information obtained from sonar.

B. Architecture

The proposed multi-robot system architecture is a centralized framework, as a means for human-conduction. This framework resulted enough to accomplish the task already presented in [12]. Furthermore, the robots are mechanically homogeneous, called Ra (front), Rb and Rc (back), and a central host. Nevertheless, at least one robot's differences (Ra:leader) arise more functional rather than physical, which exchanges its behavior for conduction. The central host deliberates the robot actions, while world sensing and data filtering are carried out by the robots. The system exhibits a non-active cooperative modality (robots cooperate with each other for guiding without knowing about the existence of the other robots).

C. Robots localization

An architectural framework embedded in each robot allows the MRS to share relative coordinates (no map of the world is required). It has been called Common Cartesian Coordinate System (CCCS) [12]-[13], whereby robots continuously share their own relative positions (via wireless). The method is based on combining measurements arising from ultrasonic range sonar and odometers. The 3 mobile robots get their pose by means of a special strategy that collects reflected points from a flat wall; if there are relative pose differences in each robot, thus the robots self-correct such differences.

D. Central host

The central host inner architecture is depicted in Fig.4, and information flow is according to the arrow-lines numeration. The central host carries out: multi-sensor data fusion; human-localization, as well as a motion-plan for the robots motor action. The part of multi-people localization was also presented by the authors in references [14] and [15]. The robots continuously request for future target-positions, where to move to while being in motion. The robots are in charge to perform: world sensing; sensor data filtering; pose ($R(x, z, \theta)$) internally performed as a background task by the CCCS; and the motion plan execution.

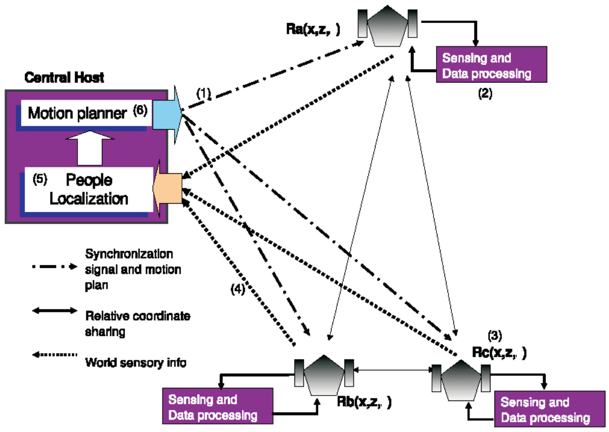

Fig. 4. Communication framework and information flow.

E. Communication framework

The MRS inner communication flows both ways, from robots to central host and inversely. Inter-robot communication is performed by means of a synchronized spreading-message paradigm for the overall trade-offs between robots and central host. It has a multicast message spreading philosophy that facilitated the implementation. The Fig.4 can be explained by the following steps which concern the flow information during the conduction task:

1) A synchronization signal t_k for sensing-start, and a motion plan is sent from central-host to robots.
2) World sensing and data filtering is carried out.
3) Robots pose estimation by the CCCS.
4) Data and robots pose are sent to the central-host.
5) People localization is carried out.
6) Based on group's center, a motion plan is generated.
7) Again from 1).

There is a network group communication (GC) with 4 members ($R_{a,b,c}$ and the central-host), which belong to the same network group; Only the central-host has membership in the 3 GC, and communication-manager controls every issue related to message spreading functions. The reason of this configuration is for having a global model representing the world; the central host essentially gathers distributed sensory data. Arrays of data are spread as messages throughout the MRS stored in a common mailbox, where the members of the MRS have memberships. Only 2 types of data are sent to the central host: (1) arrays of filtered raw data and (2) robot's pose resulting from the CCCS. In general the time spent by the data flowing in the MRS architecture for 100kb of sensory data between the robots and the central host is about 9ms. For further discussion see reference [12].

V. PEOPLE LOCALIZATION

This section explains the way how the MRS cooperatively localizes the members of a target group. The purpose is to differentiate humans from other objects in the world, and tracking each person while moving, as a preamble to determine the group's center (center of gravity CG), which its importance will be explained in later sections. Since ranged data arise from stereo vision a methodology for human localization was proposed in [14] and [15]. The method has been roughly divided as follows:

1) Sensor data filtering.
    a) Zones discrimination.
    b) Noise reduction.
    c) Quantization based filtering.
2) Multi-sensor data fusion.
3) Clustering based segmentation.
4) People localization.

Zones discrimination process is a filtering relaying on 2 thresholds (shoulders and knees) where points between them are information mostly belonging to the set of ranged people. This pre-filtering purposefully deals with the elimination of unnecessary ranged areas. Likewise, noise reduction cleans the noise produced due to light conditions and/or partial occlusion. A spatial filtering based on an XZ-window and a threshold was implemented as the solution. Further, quantization decreases considerably more the number of points to soft the computation burden. Besides, it builds a projection of the 3D data over an XZ space (2D). Multi-sensor data fusion was a gathering of sensory information into the central-host, as a way to share distributed sensor data and to represent a global model of the world overtime. Segmentation is an important issue in order to classify the objects sensed by the MRS. The method was a clustering process; it depends on a threshold distance between two 2D points. The clustering ends up with a set of sub-clusters representing the ranged objects. This method was found reliable by the authors, nevertheless different authors have proposed other reliable methodologies proposed in [16]-[19].

VI. GROUP TRAJECTORY CONTROL

Human localization has been useful: (a) to differentiate humans from other objects in the world, and to know the dimensions of the target-group; (b) to provide people's geometrical distribution to central host in order to make a motion-plan at every updating time; (c) the group's CG is estimated from members' position. Hence, in this strategy the CG is the key-issue to carry out guidance over a pathway. Trajectory control refers to how the CG is controlled for tracking the desired pathway. In essence three main elements are important for trajectory control: (a) CG observation filtering; (b) trajectory control modeling; and (c) prediction of CG at t_{k+1} by a motion model. See Fig.5.

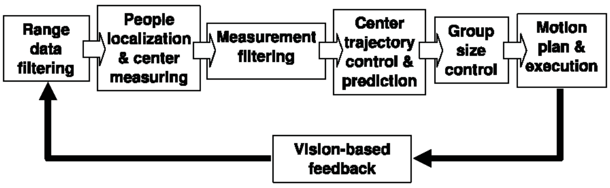

Fig. 5. Strategy for trajectory control of the CG.

A. CG estimation

Since sensor measurements are not a perfect noiseless model, the CG position is affected by a sequence of noise along each updating time. A solution to filter the CG and getting an improved estimation was by utilizing extended Kalman filtering (EKF) [20]-[22]. A projection of estimate (CG) into t_{k+1}, correlates a set of equations that expresses the dynamics of the group. Viewing the group of people as a unit, where its CG is a dynamic particle, the CG angular acceleration, angular velocity, linear velocity, and linear displacement are considered as integration in the design of the EKF system for obtaining a desired position of CG. From experiments difference between observation and estimation often reached peaks up to 5-10cm.

B. Trajectory control

The trajectory control is yielded by implicitly controlling the group's angular acceleration α. The feedback control equation $\alpha = -k_1 \Delta x - k_2 \theta - k_3 w$ regards the distance Δx of the CG toward the tracking-line, the heading angle θ and the angular velocity w. k_1, k_2 and k_3 are the constant gains set a priori.

C. CG motion model

A set of equations modeling the CG motion was proposed as the core of the trajectory control and prediction. The motion model calculates a desired next CG position as $gc_{k+1}(x, z, \theta)$ with a linear velocity v, angular velocity w, and angular acceleration α obtained from the trajectory control. All are vectorial representations except for w and α. Results from merging the trajectory control and the motion model are given in Fig.**??**.

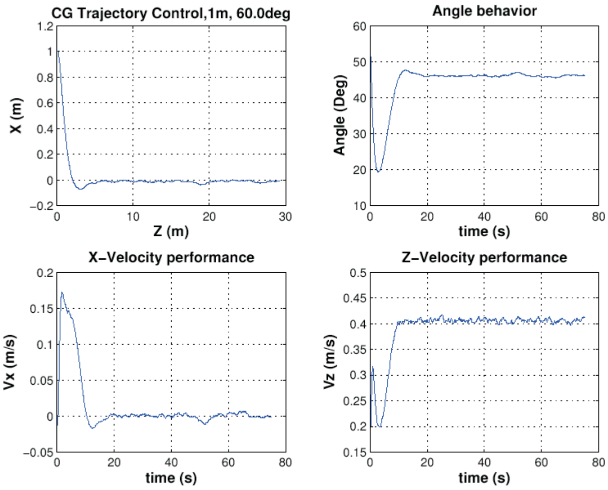

Fig. 6. Results of CG motion behavior, CG away from the pathway heading to 60, with Gaussian error included.

The Fig.**??** exhibits the CG behavior controlled at 100 cm away from the tracking-line, heading to 60^o (including Gaussian noise in the simulation).

VII. CONDUCTION AND CROWD DYNAMICS

Part of the difficulty of the problem lies in that communication between robots and humans has an implicit way. The mechanism by which guidance could be carried out depend on the fact that robots can not directly control the CG's motion variables, but could in some extent affect those values by changing the robots formation. The system has vision-based feedback for the CG control, and the w may be affected by means of continuous changes of direction during robots formation performance. It likely produces either a big or a small change of CG's θ. A circular model for representing the group scope was established and its main element for the crowding method relays on establishing a reference radius r_{ref}, whereby if the current radius $r_k > r_{ref}$, then the process of crowding is carried out forcing the people to modify their inter-spaces. Robots enclose more the group-area by speed-direction changes and advantageously reaching future desired positions. A set of motion equations for each robot was implemented in the motion planner, and robots heading anlge are established based on the next desired CG position cg_{k+1} $(Ra = 0^o, Rb = 150^o, Rc = 210^o$ respect to $cg_{k+1})$, as the core for the formation strategy. In fact, a triangular formation not only surrounds the whole group, but also attempts heading to the pathway successively.

VIII. SIMULATION AND STUDY ON PEOPLE MOTION

Until this stage experimental results by deploying the team of robots with people were obtained. However, a simulation model involving the overall situations give us several favorable points: (a) A good approach to prove the effectiveness of the proposed trajectory control; (b) verification of the method and the strategy; (c) confirmation of the control; (d) the MRS motion planning; and (e) pedestrians group motion modeling. In reference [23], an attempt to simulate crowd dynamics by pedestrians affected by the presence and introduction of mobile robots was presented. Such context considers a large number of pedestrians and few robots in order to study and understand its impact and effect in wide areas people behavior, using the Social Force Model (SFM) originally introduced by Helbing and Molnar in [24].

The present work included the usage of the SFM adapted to simulate a reduced number of pedestrians behaving in a group surrounded by a team of three robots, whereby people follows the leader robot (R_a) and affected by the presence of robots R_b and R_c. The motion of pedestrians was described as if they were subject to social forces applied to several behaviors describing the acceleration toward a desired velocity of motion following R_a; it also terms reflecting that a pedestrian keeps a certain distance from others in the group; and a term modeling attractive effects by R_a. The equations of the SFM involve:

1) A model for the desired pedestrians direction.
2) Repulsive effects (avoiding other members).
3) Attractive effects (pursuing Ra, conversing other members).
4) Models some random variations of the behavior.

The methodology for simulation is explained in the following steps: 1) An initial randomly location for the people; 2) observation of the CG is obtained; 3) the CG is estimated by the EKF; 4) the trajectory control and motion model yield a next desired CG projected into $k+1$; 5) members follow Ra's angle perpendicular line, behaving with certain speeds, directions and noise; 6) a circle models the group's scope determined by the radius of the farthest member from the CG; 7) $R_{a,b,c}$ move toward next desired positions for controlling group's size and direction; and 9) again from step 2). With this general methodology, Fig.7 depicts the simulation results of the conduction task with 5 persons, merging all the models proposed in this paper.

IX. DISCUSSION AND SOCIAL IMPACT

The proposed methodology may be the control-base mechanism for a set of potential guiding-tour applications. Only for mentioning some of them might be in case of disasters or emergencies guiding people toward safe places, guided-tours in companies, conducting herds of animals by farm-robots, to escort important/famous people

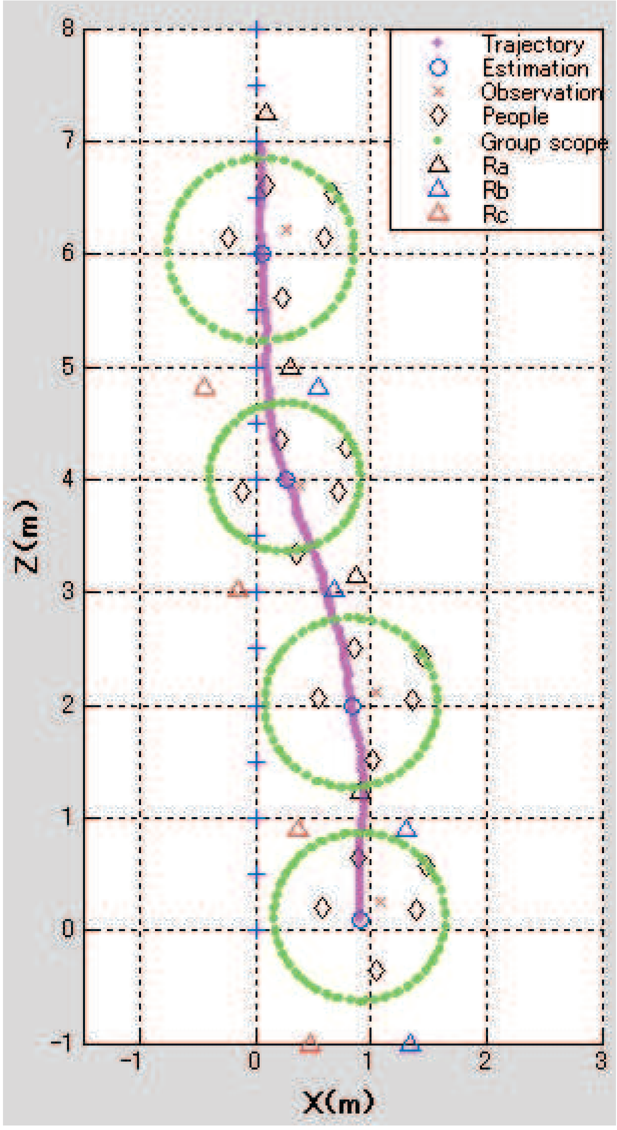

Fig. 7. Simulation results of the guiding-task for a group of 5 members.

as bodyguard-robots. Proposal of this type of guidance is featured by (a) trajectory control; (b) implicit communication; and (c) this type of guiding-tour is accomplished by three robots. Moreover, it is worth noting that some more specific issues has been considered for the study of this methodology of guidance: People assumptions, leader based robots formation, several robots surround the group of people, people walk feeling the approach of R_{b-c}, robots crowd by affecting positions and speeds, and R_a yields guidance. The strategy for people conduction has been established by 3 main points:

- Visual-based people tracking.
- MRS architecture.
- Trajectory control and motion planning.

The simulation of the overall system provides some advantages meanwhile experiments with real groups of people are more difficult to accomplish due to many factors such as human behaviors, experimentation with different social groups and so forth. The simulation provides:

- Verification of the proposed method.
- Confirmation of the CG control.
- Human-motion modeling.
- MRS motion planning.
- Simulation of other situations (e.g. obstacles, more robots, other people walking close to the group).

The authors have presented a general description on the implementation of this architectural framework. However, some ethical factors are still in process of investigation required for tackling the issues generated by human behavior, while conduction process is performed. First work on automatic flock control was presented by Prof. Vaughan in 1997 [25], flocking and directing a group of ducks by a single sheepdog mobile robot successfully. However, the present context still must include further investigation on the human-robot interaction and the issues involving social and collaborative aspects between humans and robots [26] and [27].

X. CONCLUSIONS AND FUTURE WORK

This paper has been focused on a general description of the entire research, further than the technical details. The architecture of a multi-robot system was proposed to solve a particular problem of conduction for groups of humans. A key-problem is characterized by implicit communication to accomplish steering trajectory. Research on dynamic multi-people tracking, multi-robot synchronization, keeping-formation, networked robots and motion planning has been encompassed. The application itself has been developed obtaining experimental results in each issue already mentioned as part in the hypotheses generated for this kind of guidance. Moreover, to date some experiments have been realized obtaining positive results such as people localization, data communication, multi-robots formations and localization. Eventually, some final experiments are still being undertaken with real groups of people. A future study on people ethology and humans behavior, and some other human factors are a need to give more significance to this work, and how the team of robots could approach and/or face such situations as well.

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