An Approach to Sociable Robots through Self-distributed Energy

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Abstract – Research of autonomous mobile robots has mostly emphasized interaction and coordination that are naturally inspired from biological behavior of birds, insects, and fish: flocking, foraging, collecting, and sharing. However, most research has been only focused on autonomous behaviors in order to perform robots like animals, whereas it is lacked of determinant to those behaviours: energy. Approaching to clustered animal and the higher, collective and sharing food among individuals are major activity to keep society being. This paper issues an approach to sociable robots using self-maintained energy in cooperative mobile robots, which is dominantly inspired from swarm behavior of collecting and sharing food of honey-bee and ant. Autonomous mobile robots are usually equipped with a finite energy, thus they can operate in a finite time. To overcome the finitude, we describe practical deployment of mobile robots that are capable of carrying and exchanging fuel to other robots. Mechanism implementation including modular hardware and control architecture to demonstrate the capabilities of the approach is presented. Subsequently, the battery exchange algorithm basically based on probabilistic modeling of total energy on each robot located in its local vicinity is described. The paper is concluded with challenging works of chain of mobile robots, rescue, repair, and relation of heterogeneous robots.


I. INTRODUCTION

Social” robot is originally initialized from research on natural animal behaviors. Since individuals live in society, they always keep relationship and social interaction, create group in specific norm, and adhere the convention. Initially, the term “social” robot obtains possibility of interaction between a robot with environment as well as other robots. The research on animal behaviors has been applied to many applications in fields of artificial life, distributed robotic systems, game theory, and artificial intelligence. Then, numerous achievements have been alternatively used as results for studying social behaviors in which robots are symbolic examples.

Generally, Duffy et al. [4] studies the term “social” in term of embodiment of intelligence in autonomous robots. He defines social intelligence is intelligence that lies behind group interactions and behaviors. He also divides sociality into many difference degrees of social interaction based on sociable situated agents that may cooperate in a social environment: benevolent, altruist, socially responsible, independent, antagonistic, empathy. Fong et al.[3] describes several social properties that are directly applied to scientific fields. Stigmergy principle, which is a term used in biology to describe environmental mechanisms for coordinating the work of independent actors, is more emphasized in artificial life. Similar principles such as communication, interference, and aggressive competition are developed in multi-robots or distributed robotic systems. Embodiments of self-organization observed from insect societies are further used in artificial mechanisms. They enable group of simple robots to perform difficult tasks. Recently, the term “social” robot has been changed over the years emerge more senses. Breazeal et al.[2] analyses the term “social” robot to become more strongly associated with anthropomorphic social behavior. She defines four classes of social robots in terms of supporting capability of social model and complexity of interaction scenario: socially evocative, social interface, socially receptive, and sociable. In the classification, she distinguishes “sociable” as a distinct subclass of sociable robots in which sociable is a property of robots to satisfy partly human social cognition such as drive, emotion, etc.

However, we are aware of food as essential core of animal society in which its daily activities are looking for food to exist. Therefore food is just decisive key for other activities. In the opinion we propose a definition of “sociable robots” as robots that operate in societies where individuals are capable of mutually sharing not only food, but also task, information, recognition and even intelligence to other robots. The proposal is colourfully inspired from swarm behaviors of honey-bee in which honey-bee is fairly collecting food to common nest and interesting points of strategy game in which “farmers” are working to support energy for “solders” and “fighting units”. This definition basically insists of most significance issued by Breazeal [2] but our definition is come up from the core of generally social behaviors instead of human intelligence. Social embodiment described in [4] is also emerged if robots can exist to achieve characteristics mentioned. In the project, we create group of sociable mobile robots that are fairly capable of collecting and sharing energy.
to keep group powered. The robot are all constructed in the same architectural morphology, control system, and battery exchange mechanism. Therefore, every robot has also fairly same task of carrying battery and exchanging to other robots. Additionally such robots can be assigned other different tasks depending on the environment and mission. The establishment of energy exchange among distributed robots is referred to probabilistic model in which dynamical variables are remaining energy of robots, related distances between them, absolute distance to closest full charged battery station, workload of assigned task, and history. On the horizon, we are establishing a truly autonomous mobile robot system with long-lived property conducted by probabilistic distribution among robots.

The paper proceeds as follows: In section 2 the related work of energy problems is described. In section 3 we describe the overall architecture of our mobile robotic systems including mechanical morphology, modular electronics and control architecture of functional modules. Section 4 describes the probabilistic algorithm of battery exchange. Experimental deployment and current results are presented in section 5. Section 6 issues discussion in comparison to other research. Finally, we summarize early results of the systems and give out future direction.

II. RELATED WORK

Mobile robot is now researched and used widely in many applications, such as exploring, searching, and rescue of an unknown area, or hazardous environment. However, using the law of energy conservation, we can easily see that the energy can not be created and destroyed, but it can change its form. With mobile robots, it must be necessary to be equipped with a tank of energy to power its operation until the tank must be fueled again. For examples, popular vehicles must be equipped a tank of energy to store fuel e.g. gas, petrol; the most of electric vehicles use rechargeable battery packs. Some special vehicle like robot is attached a solar cell or wind cell on the top to salvage natural sources. In fact, we know a mobile robot will have life-span of no longer than a finite time due to stored energy. Therefore, to create long-lived vehicles, the volume of fuel tank should be increased, or the fuel material should be more concentrated, or natural condition of sunlight and wind should be stable time by time. However, criteria all are impossibility fulfilled due to real limitation of tank material, size, fuel concentration, natural condition, and operation environment.

In another classical method of energy conversion, European researchers have investigated collecting and digesting food of natural animals, e.g. sugar, pistil, flies and a digestive mechanism of food to transfer naturally collected food to energy for mobile robot. Ecobot I [1,13] with a sugar digestive mechanism demonstrates possibility of the biological method. Further, Ecobot II can catch home flies, and then digests the flies and their exoskeletons transfers into electrical energy. But, sugar or flies are sources not always available everywhere.

Another approach to long-lived mobile robot is recharging stations. The approach is widely applied for vacuum cleaning robot that autonomously moves around to clean up and return to docking station to be recharged in home. Normally, such robot uses rechargeable batteries as power sources and the batteries, of course need to be charged again for a few hours. Autonomous charging docking with possibilities of sensing and communication was added to guide robot to easily reach charging points. Silverman et al [5] and Seungjun Oh et al. [6] describe their implementation in which autonomous recharging docking mechanism is specially designed with infrared proximity and laser range sensors to guide robot to go back and firmly connect with the station using landing technique of airplane. Moreover, Hada and Yuta et al. [10] give results of the week-long repetitive docking experiment. The robot is equipped infrared sensor and reflective tape on the floor to guide robot to docking station. Most difficult technique to successfully implement such systems is path planning that enables robot to contact charging station in precise direction. In the case, particle filtering [12] or Kalman filtering algorithm has been usually chosen to estimate such a path using proximity sensors. As an extension, multi-charging stations to maximize longevity of distributed robotic teams is considered in some practical cases. Nevertheless, the solution is really suitable for simple autonomous robot with low-level mission and no high demand of charging time, and traveling time from target to charging station.

Another approach to prolong longevity of mobile robot’s power source is efficient use of a finite energy amount. To save total energy of mobile robot, optimizing mechatronic devices on the robot and its motion planning to reduce operation power is world-widely considered. Conventionally, hardware configuration of mobile robots obtains embedded electronic boards, actuator and sensors are integrated to run at low speed to save energy consumption. Further, due to electronic devices always consume a finite energy even though it is not necessary to be used at a time, so that the devices should be turned off or switched to standby mode to save robot’s overall energy. For instance, Barili et al. [9] investigates concept of controlling velocities of DC-motors to save energy. But the technique is only to save overall power for mobile robot and then prolonging longevity of robot in a battery life. It is not sufficiently capable of extending or changing the total energy for mobile robots.

Alternatively, Zerowski et al. [12] proposes an interesting approach: a tanker robot that is specially deployed as “mother” robot. The robot traverses to record the temporal position of “worker” robot and then distribute energy cells to “worker” robots if demanded. This proposal is compared with daily work of gas trucks that usually deliver gas from main repository to local gas station or tanker aircraft to fighter
III. FRAMEWORK OF SOCIABLE ROBOT

A. Mechanical Morphology

In the project we have designed a standard mobile robot architecture constructed by two-wheel differential drive with two additional points of contact. Therefore, kinematic motion of the robot is only depending on kinematics sliding constraints of standard two-wheels.

![Fig.1. CAD model of CISSbot](image)

The robot, named CISSbot, is architected in two open-layers in which the lower layer contains central control system and upper layer is specially designed for battery exchange. With the open-mechanical architecture, the robot can be additionally extended with other layer due to assigned mission. For example, a manipulator is possibly attached on the highest layer of the robot to be able to scan and pick up specified objects on the floor. Since challenges in mechatronics design are towards integration of both mechanical and embedded electronics, we firstly illustrate overall architecture of mobile robot in CAD model. Due to our previous work of modular artefacts in robotics [16], we are continuously using the standard size of 9V rechargeable battery available on the market, therefore size of CISSbot is designed due to the size of 9V battery. The model of the lower layer is definitely designed to fit into motion systems of differential wheels, castors and electronic parts of infrared array, odometer, digital compass radio communication and infrared local communication. Complicatedly, the upper layer is generated with 8 parallel sliding battery holders integrated with miniature linear actuation systems and light indicators. Specially, the linear actuation system is embeddingly created to transfer the rotating force to translating force for pushing battery cells or micro-robots. To extend purpose of CISSbots, the layer is increasingly implemented with particular hook mechatronic systems for rescue solution. On real mobile robot, all parts of both lower and upper layers are assembled from pieces of acrylic plastic materials, thus it is very easy to modify or change for requirement as a result. Generally, the CISSbot architecture might partly fulfill basic criteria of flexible mobile robot that are mainly used in experiments.

B. Modular Electronics

To create central processor and functional modules of CISSbot, modular electronic circuit boards are suitably designed for purpose of such robots. As basically required for every mobile robot, the boards consist of integrated elements of central processors, sensing and actuation. In the project, we have chosen a design technique of functionally modular boards due to specialized function. The electronic boards are inter-connected to form overall architecture added-on two mechanical layers of the robot: mainboard, battery exchange, battery management, local sensing and communication, wireless communication, digital compass, infrared sensor array, and odometer. The layout of printed circuit boards (PCBs) of such elements can be seen in the figure 3.

L1) is the lowest layer under the bottom mechanical layer of the robot where infrared sensor array works as a vision system to track black or white line on contrast background to guide the robot follow the line precisely. Hamamatsu odometer is further designed to increase capacity of speed estimation of the robot.

L2) is the two miniature infrared sensor boards that is flexible design for both local communication between two robots when contacted to perform battery exchange and proximity sensing for short range measurement to avoid obstacles.

L3) is the mainboard that control the overall behavior of the robot via inter-connection. On the board, ATMEGA128 adapters are used as main processors that are inter-connected to communicate via I²C protocol. Chipcon radio communication adapter is used to generate global communication among robots as well as host computer. To provide sensing data for localization techniques, a Hitachi digital compass is additionally associated with odometer and infrared array. A motor controller is also plugged in the board to control two differential wheels. Generally, the mainboard is an open-slot board, so it is easy to expand with extra sensor or
actuator modules that will be able to be used in the future to more difficult purpose.

![Fig.3. Modular electronics of CISSbot](image)

L4) is a battery motor controller board including multiplexer 1 to 16 to reduce number of inputs to control 16 miniature linear actuators. Thus, only one H-bridge motor controller is used to control the whole process of battery exchange, inter-hooks for rescue or chain of mobile robots through encoding commands by main processor.

L5) is a battery management board that is computational electronic circuit that consists of current flow rectifier, DC/DC converter to support a stable voltage for whole electronics parts, light indicator for connected batteries, overall current limiter, multiple voltage regulator outputs for different modules, and sub-circuit of battery measurement. The Maxim chip circuit of battery measurement, which is of major importance, must indicate instantaneous values of batteries on each holder in order to decide battery exchange operation on the robot.

C. Control Architecture

We have built a layered architecture of separately functional modules for our robotic system, which is projected to hardware architecture and software organization. Characteristics of the organization are primarily based on roles of functional modules and their reciprocal relation in the system. The architecture is divided into two areas of central processing and battery exchange corresponding to mechanical morphology of the CISSbot mentioned above.

![Fig.4. Control Architecture of CISSbot](image)

The central processing includes drivers for global communication among robots as well as positioning sensor systems to localize robot’s position while the battery exchange involves driver of battery management for each battery holder, local communication and linear motor system for battery exchanging process. More details, the architecture is typically established in the manner of input-processing-output in two levels: low-level processing and high-level processing. In the low-level processing, software drivers are independently implemented for hardware modules to issue sensing data such as infrared sensing, infrared communication, wireless communication or to control actuation such as DC motors of wheels, linear motors of battery exchange and so forth. In fact, precision of the system is due to not only sensory data captured by functional sensory modules but also data fusion technique. To increase effect of sensory data, we have implemented high-level processing over the low-level processing as a middleware. In the middleware, data filters such as Kalman, and Bayesian are used to optimize precision of associated information. Point to figure 4 fuses sensory data into data association that is transferred to decision systems to issue commands to control robot behaviors. In a view, arrows in figure 4 show the interactive direction between modules.

IV. PROBABILISTIC FORMULATION OF SELF-DISTRIBUTED ENERGY
We assume that $t + \Delta t$ is time when robot $r_i$ is already recharged. The total energy of robot $r_i$ at time $t + \Delta t$ is substitution of remaining energy at time $t$ and energy consumed on traveling distance $d_{is}$ and $d_{kt}$. At time $t + \Delta t$, remaining energy of robots around the robot $r_i$ is estimated:

$$E_i(t + \Delta t) = E_i(t) - d_{is} \ast C_i(t) \quad (0.2)$$

Because every robot itself always checks battery status and keep communication with other robots in its vicinity, thus a robot $r_i$ needs to be charged if indicated by battery management system, it will search for closest charging station and other robots that can distribute energy. Thereby, we formulate local energy distribution in term of algorithm of comparison and negotiation of remaining energy of robots with respect to energy status shown in figure 5. We issue probabilistic algorithm of battery distribution for CISSbot, including two procedures: searching for closest charging station and robots in robot $r_i$’s vicinity with corresponding distances and remaining energy; and decision:

<table>
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<tr>
<th>Algorithm: BATTERY EXCHANGE</th>
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<tr>
<td>1. Initial: a set of predefined battery status { $E_{good}$, $E_{standby}$, $E_{self-contained}$, $E_{stop-working}$ }, maximum energy $E_{max}$, number or robots in a local vicinity $k$, a set $d_{ki}$ as corresponding related distance of other robots to robot $r_i$, $d_{is}$ absolute distance of robot $i$ to station and selected robot index</td>
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<tr>
<td>2. Searching: Find number of robots in robot $r_i$’s local vicinity in radius R and put into list $k$</td>
</tr>
<tr>
<td>3. Energy Calculating: calculate remaining capacity of robot $r_i$ to go back charging station: $E_{ui} = E_{ui} - d_{ui} \ast C_i$ and remain energy of the robot in the local vicinity after traveling to robot $r_i$’s position: $E_{ui} = E_{ui} - d_{ui} \ast C_i$</td>
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<tr>
<td>4. Selecting &amp; Controlling: Find the max in set { $E_{ui}$, $E_{ui}$ } to show index. If index is in { $E_{ui}$ }, guide robot $r_i$ to go back closest charging station using MOTION_PLANNING. Otherwise, index is in { $E_{ui}$ }, project $E_{max}$ to { $E_{max}$, $E_{standby}$, $E_{self-contained}$, $E_{stop-working}$ } to issue decision in set { LOW_POWER( $r_i$ ), STOP_WORKING( $r_i$ ), CALL_FOR_EMERGENCE( $r_i$ ) } before using MOTION_PLANNING, depended on current position of robot $r_i$, robot $r_{index}$, and closest charging station</td>
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V. EXPERIMENTAL DEPLOYMENT

A. Initial Scenario

In the initial scenario we intend to demonstrate our approach to probabilistic model of maintained energy for mobile robots
towards sociable robots. Thereby, we setup a simple mapping field for CISSbot experiment. The scenario is generated by a 10x10 orthogonal grid of while tapes on the black plastic carpet as figure 6.

In our system every robots is always set-up with the mission of battery exchange if demanded. So there is not specified “tasker” robot as [12], where appears the model of master/slave in which some operates as worker without mission of carrying batteries and some works as battery “carrier”, which only behaves as battery deliverer without other works. In our system, we never define the name “tasker” or “carrier”; they are temporally automatically assigned in short time, depending on probabilistic density function of total energy at a time in local vicinity. In fact, the radio communication range is much longer, the term “local” is correspondingly like “global” area, that is, each robot can communicate with others.

Thanks to infrared array of line tracking, every robot can easily follow the while line to traverse in the field. In the setup, every robot is free to move randomly to consume its own energy, instead of doing assigned jobs as proposed in the future. It sends out a radio signal of energy status and current position other robots frequently, therefore the other robots can easily update current status of robots moving around it. Thus it can distribute energy, rescue or make chain with the robots that need to be helped. Total energy of a robot is consequently synthesized and projected to corresponding rates of consumed energy tables predefined in figure 5, to give out corresponding decision for robot on state. If energy on a robot approaches to cal_for_battery, it automatically sends signal of low_power status to other robots and waiting for the reply. The other robots will analyse the signal and return a signal obtaining its current position and remain energy state. The robot will optimize replies with respect to related distances and remain energy capacities and select which “carrier” is going to exchange battery and where they must meet if there exists robots with high energy capacity in its vicinity. Simultaneously, it will compute its own remaining energy capacity to refer to distance from current position to closest charging station. If remain energy capacity can enable the robot move_back to the charging station, it itself will do to update new energy source at the best. Otherwise, the robot switches to standby mode to wait for rescuer. In that case, another robot will automatically move to the robot for battery exchange or full-haul it to the repairing station.

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In process of battery exchange, two robots will communicate to arrange temporally meeting point, and coordinately moving to the position. Then infrared local communication will conduct the exchange by selecting the holder to be changed between robots: the usable battery is moved to empty holder of the “tasker” robot; the discharged battery on the “tasker” is returned to the “carrier” if indicated. Using the principle of potential energy distribution of two essential variables of remaining energy and corresponding distance projected to Lego battery station as central point, robots that is in state of low energy and closer to charging station is nominated to become “carrier” that will move back to the charging station to return batteries drain off and take full charged ones.

B. Extented Scenario
In fact, the first setup can only satisfy requirement of industrial application that is normally deployed in manufactory or educational environment where initial conditions are obviously possible to be fulfilled up, such as grid mapping, stable environment, and even host. The extended scenario is partly to solve challenging ideas of advanced probabilistic energy distribution where host may be not used, where rescue service is experimented, and where “mother” robot can carry “microbot” with low energy capability to unknown area to deploy exploration. The
extended scenario can be also expanded to chain of mobile robot in order to make robots passing to rough terrain using smart hooks, as modelled in figure 8.

![Fig.8. CISSbot “Mother” with Microbot “children”](image)

In the case, we separate environment into three areas: working area, charging station and repairing area: the working area is place where robot is free to move or work with assigned mission; the charging station is a station where fully drained batteries are recharged and then supported to “carrier”; and the repairing station is a shed where failed robots are carried back for repairing process. To implement ability of rescue service, we have to create small hooks that are stand in front and behind sides of robot. The hook is controlled by steering gears in order to easily connect and lock to other robot, thus the “rescuer” can carry the failed robot back to the repairing station.

Moreover, a single mobile robot is be less stable to move on rough terrain or possibly pass over wide trench but a chain of mobile robot is much better to do as explained in [15]. The hook is specially made by flexible aluminum so its force is strong enough to generate a chain of mobile robots if locked to other robot. Thereby, the second robot on the chain will be probably a fulcrum for the first robot to pass wide trench.

Another property of advanced mobile robot is cooperation between heterogeneous mobile robots to archive higher results. We investigate property of animal society, e.g. kangaroo rat since kangaroo mother always feed kangaroo children and take care them in front pocket or carry them out to place of food or water. Inspired from kangaroo’s good care, we develop a mother-children relation in which CISSbot acts as “mother” and “microbot” behaves as children. To explore narrow area where CISSbot size cannot fit into, the “mother” will carry “microbot” out to the place and release them for exploration. It is impressive point that the “microbot” is charged by energy of mother on the way moving in order to save moving time and energy. At the local area, the “mother” will be mobile charging station for “microbot” when its battery is drained off.

Finally, towards world animal society by skipping the grid mapping we will try to upgrade sensor system to gain sensing possibility to avoid moving objects, localize and position for battery exchange process. Because this problem is related to high techniques of localization that is required combination of low-level processing of sensors and high-level processing of fused data, we are planning to build a system sensing of light scanning, and IR beacon for the solution. Although localization is not our research trend, the research is being still carried out in the future.

VI. DISCUSSION

In the project we propose scientific approach to energetic autonomy of mobile robot towards sociable robots. Analyzing references of current research of social and sociable interactive robots, we issues a new concept of sociable robots that we expect to become world-definition. On the one hand the concept is to slightly cover definition of sociable robot proposed by Breazeal [2] and Fong [3], since they only mention emotional, social characteristics of robot like human, and Duffy [4] since social characteristics is embodied in autonomous mobile robots.

We do not focus to perform characteristics of human-like robots, instead we adhere to social animal societies in order to point out the core of social life: food; and survival activities of social animal: collecting and sharing. In section 2, we refer too many existing research of energy for mobile robotics to show that the energy of mobile robot is definitely finite so the robot can operate in finite time and a robot is only recognized as truly autonomous robot if it can be autonomy of energy. So robot can be like predator to collect food or hunt prey, for example: Slugbot, Ecobot I and Ecobot II [1,13]. It can also change operating states to prolong longevity as explained by Barili [9]. But we prefer social characteristics of animal society in which individual has to be responsibility for survival of cluster. Zebrwoski reached the concept but only focus on relationship of members in a family: mother-children; or small society: manager-worker [12]. But we propose the concept of sociable robots in distributed society where individuals are the same and fair in mission. To survive, each individual has communicate, negociate and cooperate with others to share work, to looking for food. Therefore, we create a series of CISSbots that obtains the same mechanism of collecting and sharing energy, even though such robot can be easily to add different mechanism for other purpose. In the section 3, we describe unique mechanism of battery exchange in which energy manager is key to issue decision for robot behaviour. However, the battery mechanism is not enough to reach success of battery exchange algorithm between two robots shown in section 4, instead we have to necessarily implement a lot of sensory system: odometry to measure distance among two robots, IR array to track the way to meeting point, compass to show the direction between two robots, IR local communication to guide process of battery exchange and detecting obstacles, and RF communication to keep communicating among robots.
Techniques of sensor fusion and data association are complementary to inadequateness of hardware. This enables CISSbot work as truly autonomous mobile robots. So we wish sociable robots that are sociable with our life and help us without intervention.

VII. CONCLUSION & FUTURE WORK
This paper presents a challenging trend of mobile robot towards sociable robotics. The trend is a method of propagation of energy resources among mobile robots in order to keep group of mobile robot long-lived. The method is originally based on battery exchange between robots. To create rules of exchange, a general model of probabilistic maintained energy is established. However, the model will be able to be updatingly changed when applied for specific case. In the paper, we describe details of mechanical morphology, modular electronic and control architecture for such type of mobile robots. The analysis and establishment of decision function based on probabilistic energy distribution is specially emphasized in the paper. The initial scenario shows that the solution can be directly applied to industrial application in manufacturing or deployed for indoor environment where the robot can be also sociable.

But, as not satisfied with current results, we have been implementing more advanced aspects for such robot to propose new directions for mobile robotics. As described in the extended scenario, we are concentrating on three challenges of the system. First, we are focusing on problem of mother-children relation. The mobility of mobile robots that possibly acts as charging stations is also emphasized though intelligent algorithm of energy distribution. Secondly, we are setting up a chain of mobile robots using smart hooks. The chain is mainly expected to generate more stable possibility than single robot to pass all rough terrain. Thirdly, although it is the most difficult dimension we are towards to sensing techniques for self-localization of such mobile robot without grid mapping. All work will be modeled and deployed on our real robots for practical applications.

REFERENCES