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Cooperation of Heterogeneous, Autonomous Robots: A Case Study of Humanoid and Wheeled Robots

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***Abstract*— In this paper we present a case study of cooperation of a strongly heterogeneous robot team, composed of a highly articulated humanoid robot and a wheeled robot with largely complementing and some competing capabilities. By combining two strongly heterogeneous robots the diversity of accomplishable tasks increases as the variety of sensors and actuators in the robot systems is extended compared with a team consisting of homogeneous robots. The scenario describes a tightly cooperative task, where the humanoid robot and the wheeled robot follow for a long distance a ball, which is kicked finally by the humanoid robot into a goal. The task can be fulfilled successfully by combining the abilities of both robots. For task distribution and allocation, a newly developed objective function is presented which is based on a proper modeling of the sensing, perception, motion and onboard computing capabilities of the cooperating robots. Aspects of reliability and fault tolerance are considered.**

I. Intro

With the growing importance of autonomous mobile robots in industrial and research applications the need to execute successfully challenging missions and tasks has also grown. To fulfill a large diversity of tasks with a sufficient reliability in the robot system, teams of robots are used instead of single highly specialized robots. The majority of research in robot teams considers homogeneous robots, most of them based on wheeled locomotion. The investigated tasks differ in the complexity of structure and cooperation, starting from basic tasks as foraging [1] or exploration of an area without a specific cooperation [2] up to problems with increase in communication and synchronization demands, e.g., cooperative box pushing [3] or cooperative surveillance of an area [4], [5] or soccer playing [6], [7], [8]. A classification of different stages of cooperation is given in [9]. A homogeneous robot team is usually equipped with identical sensors and actuators which usually differ only slightly, e.g., because of different wear and tear. Therefore, the diversity of tasks which can be accomplished by a homogeneous robot team is still quite limited. This drawback can be overcome by a team of heterogeneous robots, each or several of them equipped with different sensing, perception, motion and onboard computing capabilities. Several application have been investigated with robots, which differ only slightly in their capabilities. Although these robots are not fully identical, commonly they are still considered to form a homogeneous robot team [10]. Depending on the level of heterogeneity robots in a team are classified as weak or strongly heterogeneous. An application with a strongly heterogeneous robot team has been developed, e.g., for aerial surveillance [11], where different robot types, a blimp, an airplane and a helicopter, cooperatively monitor a rural area for detecting forrest fires.

Another strong motivation for investigating cooperation of heterogeneous autonomous robot teams comes from a simple observation: In one or two decades not homogeneous robot teams will be that standard case but many different autonomous robotic systems of different generations and capabilities will have to cooperate, possibly in an ambient intelligent environment, to fulfill common tasks.

Main ideas for heterogeneous robot teams are complementary equipment in sensors, actuators and computational units to ensure a large variety of different skills in the system and concurring equipment to afford sufficient redundancy in case of failures. In addition all software components should be modular to allow the exchange of both hardware and software modules as well as an easy transfer of hardware or software components to another robotic system.

In this paper we present a new application of a strongly heterogeneous robot team, consisting of the wheeled robot *Pioneer 2dx* and the humanoid robot *Bruno*. The before mentioned concept is realized in that way, that essential capabilities such as locomotion are redundant, but differ in locomotion speed, whereas other capabilities exist complementary. As a result of the different locomotion and flexibility, the heterogenous robot team can cooperatively cover a large variety of different tasks, among them object perception, following, transporting and maneuverability as well as communication. The paper is organized as follows: First we describe the scenario, divided in tasks. Based on this the robots are characterized with a special focus on the capabilities and skills derived to fulfill the mission. The software is described with a focal point on task assignment and reliability in case of failures in the robot hardware or software.

II. Cooperative Scenario

The scenario shows a tight cooperation with autonomous mobile robots, herein represented by a humanoid and a wheeled robot. The 55 cm high humanoid robot *Bruno* [6], developed in a joint project by *Hajime Research Institute Ltd.* and *Darmstadt Dribblers*, is highly actuated by 21 degrees of freedom (DOF), however lacks on a low additional payload, which causes all on board components to be well selected with respect to small mass and as less as possible

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(a) *Pioneer 2dx* (b) *Bruno* (c) Kinematical structure of *Bruno*

Fig. 1. Strongly heterogeneous robots in this application: Wheeled robot *Pioneer 2dx* and humanoid robot *Bruno*.

additional energy supply to reduce the mass of the required batteries. The wheeled *Pioneer 2dx* by *MobileRobots* has a high additional payload and a stable, fast locomotion, but the maneuverability is compared with the humanoid robot more limited.

Both robots offer competing and complementary attributes, as both can move, are equipped with a computational unit and wireless LAN for communication with each other or other PCs. However, they have different capabilities for perception and payload. These abilities allow as well a redundant system in the central skill of locomotion as a wide range of diverse solvable tasks.

A. Scenario Settings

The mission is to find autonomously a ball and follow it for a long distance; when the ball finally reaches a target position, the ball has to be moved by a robot, in this case has to be kicked in a soccer goal (Figure 2). Different capabilities are necessary for this task: To find and follow the ball for a long distance, the robot must move reliably and sufficiently fast and be able to percept the ball; to kick the ball, the robot must execute accurately highly articulated movements. These requirements can be met best with combining capabilities from different robots. The wheeled *Pioneer 2dx* can move with an adequate high speed, however lacks on abilities of ball manipulation and object perception, whereas the humanoid robot can percept and handle the ball in the desired way, but moves in a less stable way and slower on two legs. In addition to the superior locomotion facilities the wheeled robot also offers a high additional payload, which can be used to transport the humanoid robot. Thus the scenario changes to a tight cooperation task, where the humanoid robot is carried by the wheeled robot, commands it to follow the ball and executes finally the kicking motion.

To achieve a fast accomplishment of the whole mission, the base parts

- **Ball Finding and Following**: Ball search and following
- **Positioning for Kick and Kicking**: Ball kicking

are enlarged for a team of heterogeneous robots with different capabilities, namely fast reliable locomotion and additional payload, to

- **Boarding**: Boarding of one robot on another robot (Figure 2 (a) - (c))
- **Ball Finding and Following**: Ball search by one robot and transportation of this robot by the other robot (Figure (d))
- **Positioning for Kick and Kicking**: Ball kicking by one of this robots (Figure (e) - (f))

An optimal assignment of the tasks to the robots is based mainly on the capabilities available on the robots as well as the load of the robots. All tasks in this mission are executed in a tight cooperation, where the robots communicate permanently to achieve a successful result and exchange information on perception and behavior.

The software in the scenario is implemented in a robust way. The robots adapt on small failures in the environment settings or sensor data information. If one of the capabilities on the robots is lost during the accomplishment so that a task cannot be fulfilled, the robots will start a re-assignment of the tasks to find an alternative way of a successful finishing. The implementation is described in a more detailed way in Section IV.

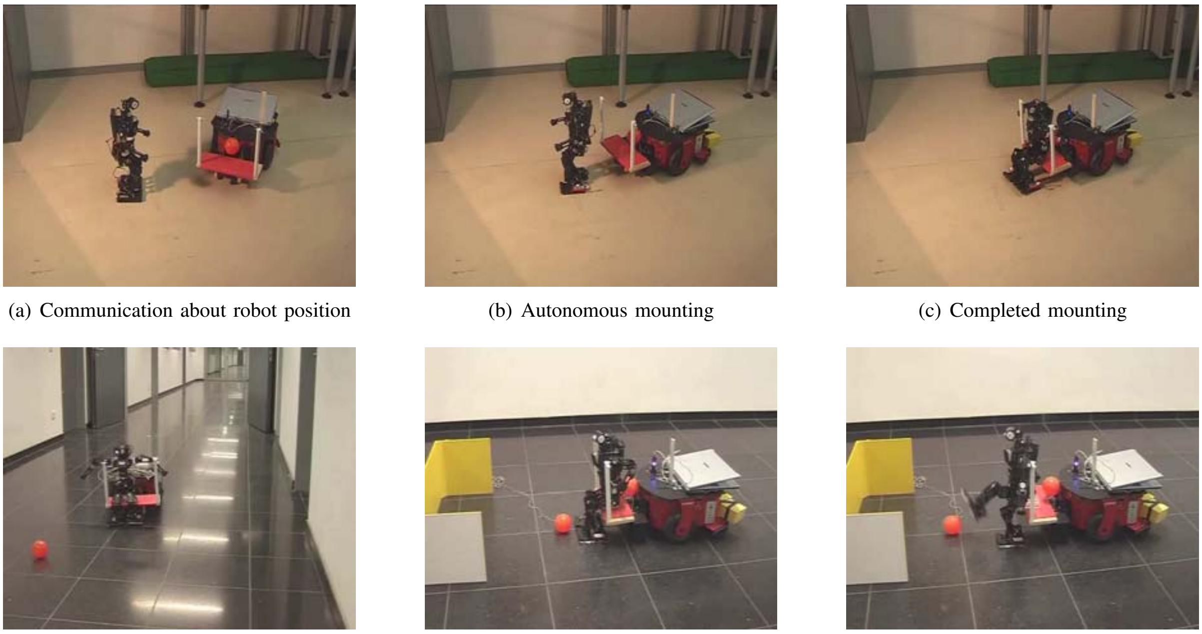
This scenario describes only one case study for the presented heterogenous robots. The system is adaptable to a wide range of different tasks, as given by combination of locomotion, object recognition and manipulation, inter-robot-cooperation and the sensor system. Also the framework, the modules for task and the behavior are not limited to this scenario, but scalable to more tasks and more robots.

III. Heterogeneous robot systems

Nowadays used heterogeneous robots consist mostly on wheeled and legged robots. Some applications with flying systems or track vehicle are used in outdoor scenarios, however these robots are not designed for a daily use in a human environment, which is often indoor. Based on this background the herein used robots are chosen to cope with indoor applications.

A. Humanoid robot

The presented humanoid robot *Bruno* (Figure 1(b)) is equipped with 21 non-redundant servo motors (6 in each leg, 3 in each arm, 1 in the upper body and 2 in the head, see Figure 1(c)) to reach a maximum of mobility with concurrent requirement of a minimum of weight caused by the motors. The total mass of the robot is 3.3 kg at 55 cm total height. It is designed in a lightweight manner, which refers to mainly



(a) Communication about robot position (b) Autonomous mounting (c) Completed mounting

(d) Ball Following (e) Preparation for ball kicking (f) Fulfilled task of kicking

Fig. 2. Mission accomplishment: The humanoid robot mounts the wheeled robot (upper row) to follow a ball in a fast and reliable way and kicks it finally in a goal (lower row).

small robotic systems with a small additional payload and the requirement of stabilizing locomotion dynamics using inertial sensors like gyroscopes and accelerometers. The robot is extended with two off-the-shelf CCD cameras with different lenses, however in the presented scenario only the articulated head camera with a view angle of 45 deg is in use. It enables the perception of small or far away objects, whereas the wide-angle camera in the chest is not necessary for object recognition in the discussed scenario and for reasons of savings of computing time not connected in the running application.

To reduce the mass and the costs of the robot it is equipped with a minimal set of inertial sensors, which enable the robot nevertheless to walk in a robust way and execute versatile motions stably. The three axes accelerometer and three one axis gyroscopes stabilize the walking motions on a rate of 100 Hz.

The robot is powered by batteries with 14.8 V for the motors and 7.4 V for the controller board.

The control software is executed on an off-the-shelf Pocket PC with a Intel PXA272 processor with 520 MHz, 128 MB SDRAM, 64 MB Flash ROM, and integrated power supply. The operating system is a real-time Windows CE. Further on the Pocket PC is equipped with a display and touch screen to enable on board debugging, a USB (Host, Client) and a serial interface as well as wireless LAN. Additionally, the robot is provided with a 32bit micro controller board for the motion execution with 50 MHz. These both systems are separated to meet the requirements of real time motion execution.

Further information on the humanoid robot are specified in [6].

B. *Wheeled robot* Pioneer 2dx

The *Pioneer 2dx* by *MobileRobots* is a differential drive platform with two drive and one rear caster. The maneuverability in 2D is high, as it can rotate in place moving both wheels and go on flat floor with a speed of up to 1.6 m/sec, with additional payload slower. The robot is equipped with a gripper with maximal span of 21.5 cm. With an additional payload of 20 kg, the robot is able to carry among other a standard laptop as computational unit, connected via RS232, instead of a lightweight built-in onboard computer, which provides a faster processor, namely 1.86 GHz with 1 GB RAM, and more comfort in developing with a monitor and keyboard. With the gripper the robot can lift objects with a mass of maximum 2 kg and carry of at least 3.5 kg. The gripper can be extended by a seat for the humanoid robot. The power supply is given by two 9 V lead batteries. In this scenario the camera on the wheeled robot is not used to create a more heterogeneous robot system in combination with the humanoid robot. For higher navigation tasks the robot is equipped with a sonar ring consisting of 16 units with a rate of 25 Hz.

C. *Complementary and competing capabilities*

The herein presented robots offer both complementary and competing abilities. Complementary capabilities enlarge the diversity of solvable tasks. In the presented team the majority of the capabilities are complementary, e. g. object perception or transportation. Only the main skill locomotion is redundantly available on both robots. So a failure on one of the robots can be compensated by the other. The qualitative rating is given in Table I.

TABLE I

SELECTION OF COMPLEMENTARY AND COMPETING ABILITIES ON HUMANOID AND WHEELED ROBOT WITH A QUALITATIVE RATING.

robot type	locomotion	object perception	transportation	communication
wheeled	++	-	++	++
humanoid	+	++	-	++

TABLE II

SELECTION OF ABILITIES WITH A QUANTITATIVE RATING. THE WEIGHTS VARY BETWEEN 0 (VERY BAD) AND 1 (VERY WELL).

robot type	locomotion	object perception	transportation	communication
wheeled	0.7	0	0.9	1
humanoid	0.4	0.7	0.1	1

Based on this qualitative ranking a quantitative rating with weights is developed, which is used for the the task assignment. Each capability on one robot is weighted by a factor between 0 (very bad) and 1 (very well), see Table II. The identification of the values is based on expert knowledge of the robots. The skill *communication* is assumed to be very well, otherwise a cooperative scenario is not solvable. All the values can be updated online, if failures occur. If a component fails during the task execution a re-assignment of the tasks must be made.

Due to the modular assembling of the robots, both in actuating elements, sensors and computational power, the tasks are not limited to the herein presented scenario, but also adaptable to other case studies.

IV. APPROACH

A. General requirements on robot software

Our software for a team of mobile autonomous robots features a platform independent modular software architecture and platform independent modules for sensor data processing, planning and motion control [15]. The aim is a flexible adoption to changing hardware like processors, cameras or locomotion system. High level communication between modules on different abstraction levels of the control architecture within one robot system is offered as well as communication via wireless LAN between computers and different heterogeneous robots, which is indispensable in a complex cooperative scenario with exchange of sensor data, world model information and behavior decisions later described in this section.

In addition to these general software requirements for teams of heterogeneous robots the tasks in a mission shall be distributed between the robots in an optimal manner with respect to the capabilities of each robot to fulfill this task, importance of the task for the whole mission and time to execute the task.

The team shall be able to handle the mission in a reliable way, meaning that failures of a sensor or actuator component can be detected and compensated by an online re-assignment of the tasks.

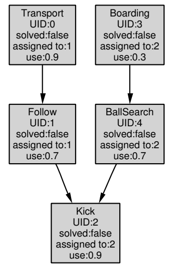


Fig. 3. Graph with assigned depended tasks for the presented mission.

B. Task modeling and assignment

The mission is separated in tasks, which can be executed by one robot. The decomposition of the mission shall be organized with expert knowledge, which justifies a user-defined decomposition as done in most projects [3], [12]. The tasks can be modeled as dependent tasks, which have a child and/or parent task and are connected via time by them, or a independent tasks, which can be executed on their own. Dependent tasks are also used to model a cooperative parallel execution of several tasks.

All tasks are classified based on the capabilities, which are necessary to fulfill it successfully. Each task demands one or more capabilities, which are offered by the robots, weighted with a factor. It has an factor of usefulness, which ranks important tasks higher, when they are assigned to robots. The task assignment is executed based on an objective function. For each task t_k a utility value $u(k,i)$,

$$u(k,i) = \sum_{l=1,m} c(r_i, a_l)$$

is calculated with $r_i,\ i = 1, ...n$ the robots in the cooperation, $a_l,\ l = 1, ...m$ the necessary abilities to fulfill this task and $c(r_i, a_l) \in [0, 1]$ the characteristic of robot r_i and ability a_l. The task is assigned to the robot, which is best qualified, means highest utility value $u(k,i)$ for task t_k and robot r_i. If more than one robot is optimal, than the robot r_opt with the lowest task load $load_i$ and the smallest robot number is chosen:

$$r_{opt} : u(k, opt) = \max_{i=1,...n} load_i \cdot u(k,i)$$

with

$$load_i = \frac{(m_{all} - p_i)^2}{(m_{all})^2}$$

with m_{all} the number of all tasks in this mission and p_i the number of tasks assigned to robot r_i up to now.

Tasks are modeled with different state of execution (assigned, solved) and a maximum of feasible time for execution. If a task is assigned and not solved after this time, a reassignment is started, because probably the task cannot be solved by the currently selected robot. The assigned tasks for the presented mission are described in Figure 3.

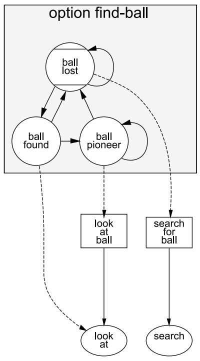


Fig. 4. Option graph for humanoid robot.

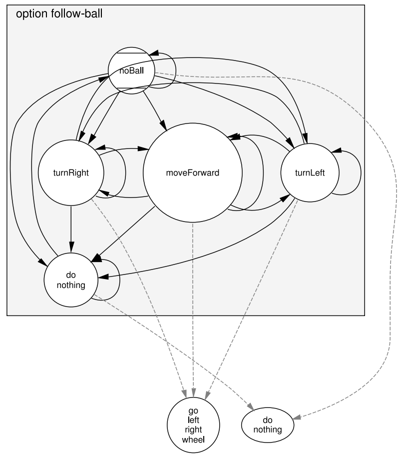


Fig. 5. Option graph for wheeled robot.

C. Behavior Modeling

The behavior executed on the robots is implemented in the language *XABSL* [13], which is a tool for engineering the complex deliberative or reactive behavior structure of autonomous robots. It is based on hierarchies of finite state machines, which are separated in agents, options and basic behaviors. An agent represents the complete mission, whereas the options in this agent are the different tasks. In the smallest unit *basic behavior* a locomotion or a output signal can be implemented.

As an example the option graphs in the part *Ball Finding and Following* for the humanoid and wheeled robot are described in a simplified way.

In the option *find-ball* in Figure 4, executed by the humanoid robot, the robot searches for the ball. If a valid ball is recognized in the camera image, the position of the ball and a reliability, which depends on the recognition quality in the image, is communicated to the wheeled robot. The humanoid robots starts the option *look at ball*, which controls the head motors to keep the recognized ball in the middle of the camera image. When the ball is lost, the behavior calls the option *search for ball*, which makes the head camera follow a way path. This way path is precalculated to cover the area in front of the robot, where the ball is supposed to be.

The option *follow-ball* in Figure 5 describes the behavior of the wheeled robot, which goes according to the communicated position. It can move to both directions with different turning angles depending on the ball position resp. go forward. In case no position is communicated within a certain time the wheeled robot will stop and only starts again, if the ball reliability is high enough.

D. Simulation

A recently developed real-time simulator [14] enables realistic environment settings, e.g., with different light conditions and color perception. So the resource *robot* can be saved, when the algorithms are tested first on a PC instead of real robot hardware. The wheeled robot is modeled with two wheels and an articulated 2-axes gripper. The humanoid robot is constructed with 21 articulated joints and a camera with the real world focal length and distortion.

The verification of the software, both algorithms and simulator, is done compared to the hardware. The picture series in Figure 6 describes the part *Boarding*, where the humanoid robot recognizes the pose of the wheeled robot with a color-based perception of the red color of the wheeled robot and the orange color of a marker on the wheeled robot. The wheeled robot turns based on the communicated pose until the orientation is correct for the humanoid robot to mount on it. The humanoid robot can calculate the distance to the wheeled robot with a size-based projection of the recognized orange marker. The recognition of the wheeled robot is robust enough for differences in the size of the recognized red area of the wheeled robot.

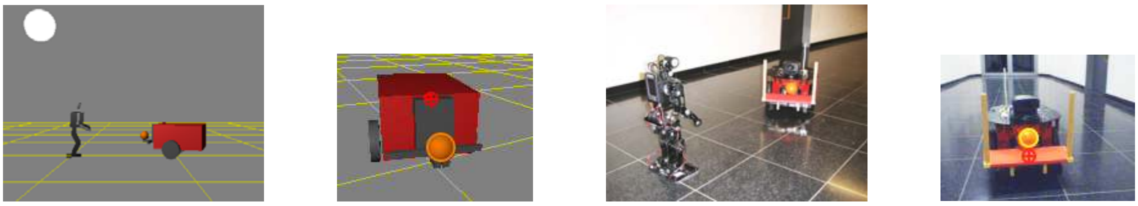
The results of the simulated and real scenarios in Figure 6 (a) and (c) are comparable, both images of the cameras (simulated in Figure (b) and real in Figure (d)) show the marks for the objects of interest, the wheeled robot and the orange marker. The verification of the algorithms both in simulation and hardware is successful.

E. Reliability and fault tolerance

The system is configured in such a way that the reliability is as high as possible, based on competing abilities in the system. If one component fails, it can be replaced by the adequate part on another robot. However, to ensure a large variety of solvable tasks, the number of complementary abilities is kept high at the same time, so not all robot abilities can be hold competing and redundant, if the sensor and actuator equipment on a robot is limited. But these complementary abilities can be used to create different ways of task solving, not by sheer substituting, but by combining other robot abilities to solve the task in an alternative way. So the system reliability can be heightened on two ways, if the implemented behavior is designed in the right way.

The software also covers small errors and failures, e.g., in environment settings or sensor data information. The robustness of the implementation permits a higher rate of successful executed tasks.

The high cooperative characteristic of the mission requires a robust implementation of the communication between the



(a) Simulated task of mounting the wheeled robot, scenario

(b) Simulated task of mounting the wheeled robot, perception of head cam

(c) Simulated task of mounting the wheeled robot, perception

(d) Simulated task of mounting the wheeled robot, perception

Fig. 6. Results from simulation and real environment: Results for the task *Boarding* (perception of the wheeled robot by the humanoid robot) are comparable in simulation and hardware.

TABLE III

RUNTIME MEASUREMENTS FOR A SET OF DEPENDENT TASKS AND INDEPENDENT TASKS, BOTH EXECUTED IN SIMULATION AND ON A REAL SYSTEM WITH PDAS.

	dependent tasks		independent tasks	
Simulation	∅ 4 ms,	max. 31 ms	∅ 5 ms,	max. 15 ms
1 robot	∅ 13 ms,	max. 25 ms	∅ 5 ms,	max 11 ms
3 robots	∅ 14 ms,	max. 24 ms	∅ 11 ms,	max. 12 ms

robots. If the needed communication fails, the robots have to react fast. For example, in the part *Ball Finding and Following* the wheeled robots reacts with an emergency stop, if it gets no coordinates to navigate to, if the communication with the humanoid robot is interrupted.

V. RESULTS

A. Runtime in Task assignment

The runtime measurement for task assignment has been tested for two different types of tasks: Three dependent tasks with 10 subtasks each and 10 independent tasks. The measurement in Table III has been accomplished both for simulation on a Windows XP Laptop (1.6 GHz) and a real system on PDAs with Windows CE (512 MHz).

B. Mission accomplishment on video

In the submitted video the successful accomplishment of the mission is presented. The whole task is finished within about three minutes, in which the humanoid robots is boarding on the wheeled robot, follows the ball with the wheeled robot in a circa 15 m long corridor and finally kicks the ball into a goal.

VI. CONCLUSIONS

A new scenario for cooperative mission achievement by a team of strongly heterogeneous, autonomous robots, a humanoid and a wheeled robot, has been presented and successfully investigated. The investigated and applied methodologies aim at more general problem classes for which the present scenario serves as a benchmark problem.

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