



Human–Robot Cooperation Using Multi-Agent-Systems

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Abstract. In this paper a new intelligent robot control scheme is presented which enables a cooperative work of humans and robots through direct contact interaction in a partially known environment. Because of the high flexibility and adaptability, the human–robot cooperation is expected to have a wide range of applications in uncertain environments, not only in future construction and manufacturing industries but also in service branches. A multi-agent control architecture gives an appropriate frame for the flexibility of the human–robot-team. Robots are considered as intelligent autonomous assistants of humans which can mutually interact on a symbolic level and a physical level. This interaction is achieved through the exchange of information between humans and robots, the interpretation of the transmitted information, the coordination of the activities and the cooperation between independent system components. Equipped with sensing modalities for the perception of the environment, the robot system KAMRO (Karlsruhe Autonomous Mobile Robot) is introduced to demonstrate the principles of the cooperation among humans and robot agents. Experiments were conducted to prove the effectiveness of our concept.

Key words: human–machine interface, man/machine interaction, man/machine interfaces, manipulation, robotics.

1. Introduction

In the past, the main goal of automation was the construction of systems excluding the involvement of humans. Man has been considered as the weak point in the operation of automatized systems: he is subject to errors, suffers from fatigue and often has an unreliable memory. In the best cases humans have been regarded as obstacles in an automatized manufacturing rather than as active factors. In fact, to guarantee the safety of humans within the working area of a robot, additional sensors and equipment are required, which would increase the cost of an automatic system. Therefore many efforts have been made to separate the working area of robot systems from man.

But today the demands for high flexible robotic systems, which must have the capabilities of adapting themselves to an uncertain environment, are rapidly increasing. This is the case not only in manufacturing, where customer requirements have to be met, new technologies should be integrated, products and propositions of each customer must be identified and individualized, but also in the services, where robots have to move in unstructured and changing environments.

Because of these requirements it is unrealistic to consider a fully automated factory or service facility. Furthermore the trend consists of integrating the man in the production process. In this context, the human–robot-team has an important role to play in this context. The main idea is to combine the complementary capabilities of robots and humans. The robot is quicker and more reliable but relatively inflexible, while the man is flexible but often unreliable. The human–robot cooperation can be considered as one of the solutions for meeting the future requirements in the industry and services.

Robots are facing new application areas in service sector. There is a need of robots for medical surgery [8], hotel trade, cleaning of rooms or household [25]. Contrary to industrial robots, which are working in a well known environment and used by skill operators, it is not the case for service robots. Service robots have to work in a “turbulent” environment, where objects are not necessarily known or have not “a priori” known locations nor trajectories.

In spite of promising researches in the field of artificial intelligence, autonomous robots have still difficulties to execute complex tasks in “turbulent” environment. The more autonomous the system is, the more structured the world model should be, and the more specific its tasks are. A small deviation between the world model and the real world causes the system break down. As a result autonomous robots suffer from typical domain restriction (Figure 1(a)). Up to now it is still not known how to achieve complete autonomous execution of complex tasks in unstructured environment [5].

A possible compromise to avoid the domain restriction problem is to find the right balance between robot autonomy and human–robot-interaction. We do not try to eliminate the uncertainties in the environment nor increase the intelligence of the robot. The main idea is to compensate the uncertainties in order to avoid the robot to become stuck or trapped by an appropriate mixture of robot intelligence, knowledge about the environment and human–robot interaction (Figure 1(b)). Through

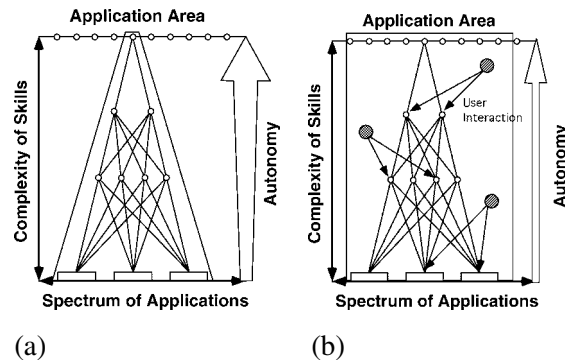


Figure 1. Domain restriction problem [22]. (a) Intelligent control in autonomous systems; (b) interactive control in service robots.

appropriate interaction it is possible to combine the complementary capabilities of human and robot in order to execute a complex task [9].

In this paper we present a very simple and intuitive human-robot interface based on human-robot interaction through direct contact. The principle consists of sharing the control of a manipulator between the operator and the Intelligent Control System (ICS) of the robot according to the context of the action, the capabilities of the human and the capabilities of the robot. Under capabilities we understand sensing, actuating as well as cognitive capabilities about the environment and the task.

2. State of the Art

2.1. USER INTERFACE

Usually the human-robot-“interaction” is restricted to a human-robot communication through keyboard and joystick [13]. But this kind of interface is not intuitive for human, does not exploit the complementary capabilities of human and robot (especially the high temporal and spatial perception capabilities of humans) and offers communication possibilities only from the human to the robot. Another common user-robot interface is an haptic interface like a 6D Mouse with bilateral feedback. Thus the operator receives an information feed back about the forces applied from the environment to the manipulator. But in general it is not an easy task for an operator to control a manipulator with a lot of degrees of freedom with such devices. These methods are not appropriated for people who have no knowledge about robotic systems.

2.2. HUMAN-ROBOT INTERACTION

In recent years new human-robot interfaces based on direct interaction through contact has been tackled by many researchers. An important issue in this area is the arm-manipulator coordination for the load sharing problem. For the cooperative motion control of a robot and a human the human characteristics are approximated by an impedance model in [10]. In [2, 3] a variable compliance control as a coordination mechanism for the arm and the manipulator is proposed. In [19, 30] a control scheme was proposed to accomplish the coordinated task execution of a human and a mobile manipulator. The majority of these works on arm-manipulator cooperation however focuses only on the dynamics of the arm-manipulator chain. Hence there is no a priori planning used for the robot, it plays a passive role and it does not recognize or interpret the action of the human according to the current situation or task context.

An other important issue in this area is the shared guidance of an object by the operator and the robot. This problem is addressed especially by the so-called “Synergistic devices”. Synergistic devices are intended for cooperative physical interaction operator by producing forces. They allow the operator to have control

of motion within a particular plane, while the device dictates motion perpendicular to that plane. Detailed description of the synergistic device COBOT for manufacturing applications is given in [20]. An overview of such devices in medicine is given in [27].

2.3. LIMITATION AND REQUIREMENTS

From the communication point of view the interaction between human and robot have to fulfill the following two requirements:

1. *Task definition.* The operator should be able to define on-line and in a simple way the task which should be executed. The definition of a task can be divided into task specification and task description:
 - *Task specification.* The operator provides the parameters, which are necessary for the task execution. In our case parameters are the objects to be handled or their locations.
 - *Task description.* By describing the task the operator gives instruction to the robot, about how to solve a specific task. In our case the task description occurs by selecting appropriated elementary operations and ordering them in the time space.
2. *Dynamic function allocation.* Function allocation is one classic question of human-machine interaction [4]. One major characteristic of this process is non-stationarity. Therefore it is vital to consider the dynamics of such a process at the same time as we consider the nature of the mutual sharing [7].

Unfortunately these requirements are neglected in the works described in Section 2.2. In the next section we present a new concept which allows the operator to specify on-line a *pick and place task* by direct contact interaction with the manipulator. The nature of the interaction between the operator and the robot changes according to the evolution of the task.

3. Analysis of the Problem

The performance of any complex system depends on the interaction between its components. To make robots capable of working together with men in different domains like transportation, assembly, maintenance and other services, it is necessary to understand the nature of interactions between the human and machine components. Robots are considered as intelligent autonomous assistant of humans, which can mutually interact on a symbolic (exchange of digital messages on a network) and a physical level (visual, tactile, acoustic). Interaction can be achieved with three concepts [29]:

3.1. COMMUNICATION

The communication between robots and humans comprises the transmission of the information at the physical level and the interpretation of the information.

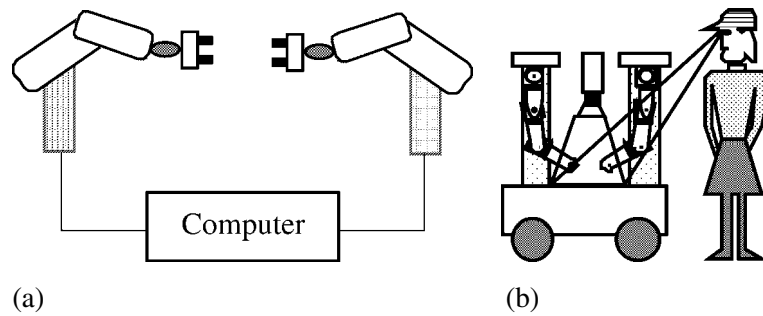


Figure 2. (a) Communication at the symbolic level in the Robot-Robot Team; (b) communication at the physical level in the Human-Robot Team.

Transmission of the Information at the Physical Level

The transmission of information from one partner to another occurs through predefined interaction patterns or protocols, which allow the receiver to understand the intention of the transmitter. Communication transmission of digital data, which enables robots to communicate with each other in normal cases, is however, no longer sufficient in the case of the human-robot-teams (Figures 2(a) and 2(b)). Within the team, the communication at a physical level, such as contact forces, must also be involved. The sensors should be used not only for the task execution, but also to recognise situations of possible interaction with other agents and to receive the transmitted information as well.

Interpretation of the Transmitted Information

The interpretation makes sense out of the transmitted information (Figure 3). Particularly for the human-robot cooperation, it is very important to avoid interpretation errors to prevent the human from danger. The transmitter should make sure that his intentions are clear enough to the receiver. For the human the confirmation of the good interpretation of the intention is reached through analysing the implicit behaviour of the partner as defined in [17]. But this is possible only if the behaviour of the partner is not ambiguous. Particularly, the robot has to perform human-like motions [12] and to exhibit reflexes similar to those observed in humans: like retracting an arm when it hits something.

3.2. COORDINATION

Several agents can have overlapping working spaces. In order to avoid mutual disturbance and conflict between two working agents and prevent the system from dead-lock, it is necessary to plan, to order or to coordinate the activities of these agents during an action.

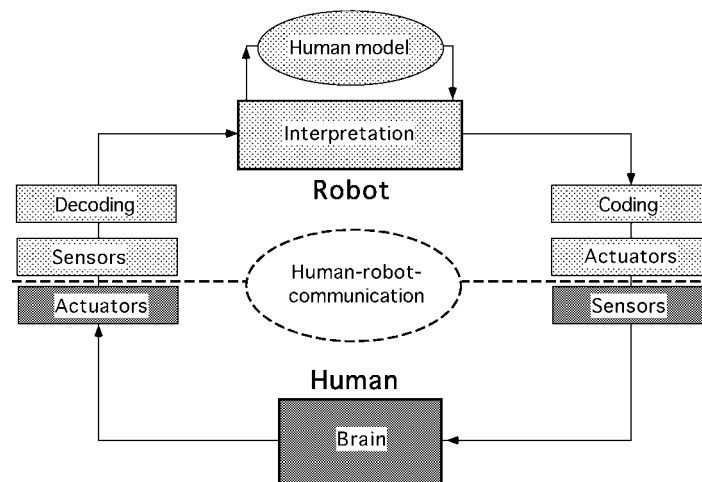


Figure 3. Interpretation of the information received by the robot.

3.3. COOPERATION

Many problems cannot be solved by single agents working in isolation, because they do not have all the necessary expertise, resources or information. On the other hand, it may be impractical to assign permanently all necessary tasks to a single agent, because of historical and physical constraints [11]. This explains the necessity of temporary alliances through cooperation where each partner contributes with his specific capabilities to the accomplishment of the final goal.

The question of human safety becomes increasingly important as future robots will be required to share their working area with human operator. The following issues have to be considered: What are the requirements on the hardware and on the software? What are the possible dangers for the human? How can the robot recognize the danger? How should the robot react in dangerous situations?

Standard benchmark problems and algorithms to evaluate the cooperation between the human and the robot have to be defined. Formal metrics to evaluate the progress made have to be developed.

4. Multi-Agent System for Human–Robot Cooperation

In our Institute several experiments have been made with the mobile two-arm robot system KAMRO (Karlsruhe Autonomous Mobile Robot). The robot consists of a mobile platform with an omnidirectional drive system using MECANUM wheels and two PUMA manipulators with 6 degrees of freedom mounted in a hanging configuration. It is also equipped with a multitude of sensors: one over-head camera, two hand-cameras, force/torque sensors on each manipulator and ultrasonic sensors on the mobile platform (Figure 4).

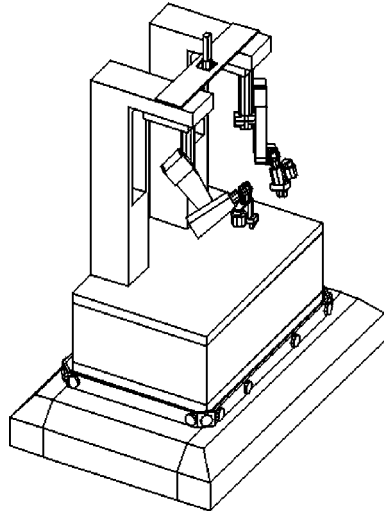


Figure 4. KAMRO (Karlsruhe Autonomous Mobile Robot).

The experiments made with the mobile manipulations demonstrate the principles of the communication between human and robots at the physical level. An operator guides the two manipulators of KAMRO by moving manually the end-effectors with his arms. The operator has just to concentrate on positioning the end-effectors, whereas the robot takes care of the collision avoidance between the two manipulators. Besides, the mobile platform must ensure that the two manipulators are always in a region of optimal configuration [18].

The experiments made with KAMARA (Figure 5) demonstrate the validity of the developed multi-agent model and the high flexibility of this architecture, which allows dynamical reconfiguration of the agent-team for cooperation and coordination [16]. Furthermore, the communication protocol on the symbolic level and the negotiation between the autonomous agents are adapted for the human-robot communication.

Based on these works, further studies must be done to demonstrate the human-robot-cooperation within the multi-agent system:

- Extending the communication model to the physical level and extending the perception methods through the fusion of various sensors, for example by combining the force/torque sensors data with the vision sensors data.
- Analysing and modelling of the human behaviour to create a knowledge base for the agents. This knowledge base will be used for implicit communication, so that the human can control the robots without any additional information about the system and can thus concentrate himself only on the important aspects of the executing task.
- Interpreting the intention of sensor data with the help of the created knowledge base. To guarantee the reliability of the interpretation, it is important for the agents to have abilities for error detecting and self-readjusting.

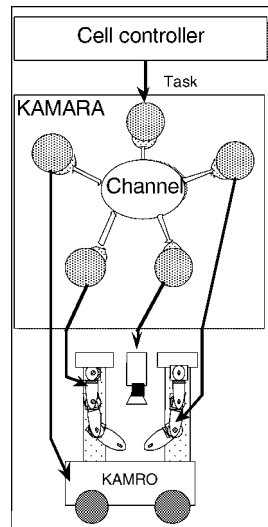


Figure 5. Distributed control architecture KAMARA (Karlsruhe Multi-Agent Robot Architecture).

- Developing a human agent and integrating it into the multi-agent control architecture KAMARA by constituting the human–robot-team.
- Analysing the safety requirements and presenting corresponding methods to meet them.

5. Overview of Our Concept

Our approach is based on the integration of human–robot cooperation in a task plan. However this plan tolerates some degrees of uncertainty and gives some degrees of liberty to the human, who is able to specify on-line some task parameters and recover system errors.

5.1. OPERATION CYCLE

A typical task for a manipulator is a *pick and place task* and can be achieved directly by one operation cycle (Figure 6). An operation cycle means the following Elementary Operation (EO) sequence which appears in robot programs frequently and is described in Table I [6].

The correct execution of this operation cycle requires sensing and actuating capabilities as well as a knowledge database. These capabilities are useful in order to sense the state of the dynamic environment, avoid collision with the environment, find the position of the workpiece, grasp the workpiece correctly, compensate the uncertainties about the environment.

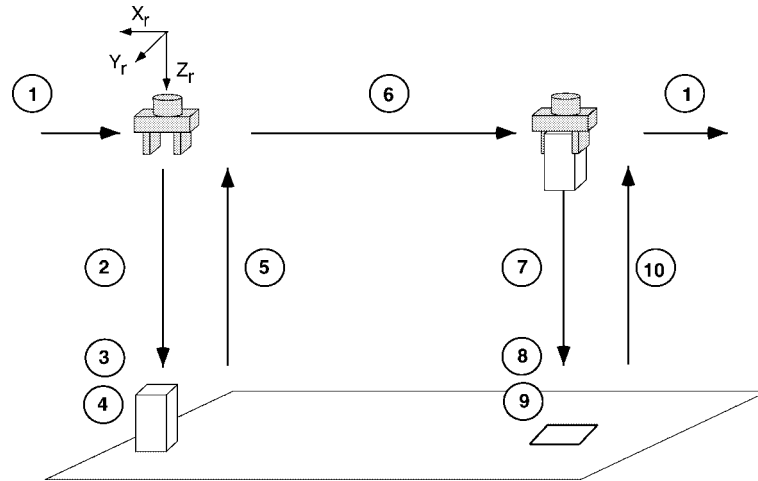


Figure 6. Representation of an operation cycle.

Table 1. Description of an operation cycle

EO 1	Moving an arm without holding a workpiece
EO 2	Approaching the workpiece with the gripper
EO 3	Grasping the workpiece
EO 4	Separating the workpiece from a base plate, a fixture or from another object
EO 5	Departing
EO 6	Moving an arm which holds a workpiece
EO 7	Approaching the workpiece to another object
EO 8	Establishing a defined contact to this object
EO 9	Ungrasping the workpiece
EO 10	Departing

5.2. ERRORS IN UNSTRUCTURED ENVIRONMENT

According to our previous experience with the autonomous robot KAMRO (Karlsruhe Autonomous Mobile Robot) we have to admit that in spite of all the efforts made to develop an highly fault-tolerant control architecture it still remains some errors, which cannot be easily overcome. A Classification of possible errors, distinguishing between internal robot errors (mechanics, control, algorithm, model...) and external errors (sensor) and cognitive errors (database) is given in [24]. A possible solution to overcome these errors is to integrate the human in the “control loop” and give him enough “degrees of freedom” to solve the conflict between the internal representation of the world and the real state of the world.

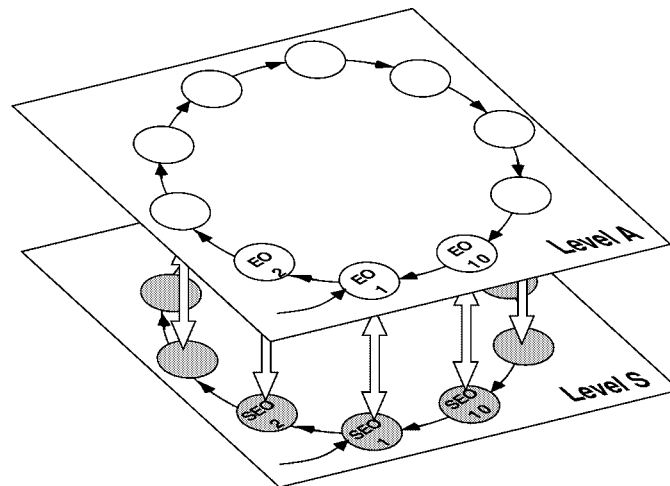


Figure 7. Integration of the human-robot interaction into the task plan.

5.3. DESCRIPTION

In order to integrate the human in the “control loop” of the manipulator we define for each situation of the *pick and place* task symmetrically to the EOs, which are executed automatically, the semi-automatic elementary operations SEOs. When the robot is not able to accomplish the required task autonomously, it switches into the semi-automatic mode and gives then the operator the possibility to help him. The integration of these semi-automatic SEO into the operation cycle is shown on Figure 7. We distinguish two levels for the task execution according to the degree of autonomy of the robot: the level A represents the autonomous level S whereas the level represents the semi-autonomous level. The events which activate the transition between the two levels are represented by the white arrows. The nature of these events will be discussed in the next section.

In the semi-autonomous mode the control of the degrees of freedom of the manipulator are shared by the human and the ICS. This is what we call “control allocation”. To enable the shared control of a manipulator between the humans and the ICS in the semi-autonomous mode we separate the coordinates into the coordinates controlled by the human and the coordinates controlled by the ICS. To each SEO corresponds a predetermined control allocation. This control allocation is defined according to the capabilities of human and robot. A given degree of freedom is controlled by the “partner” of the human robot team, who has the best sensing, actuating or cognitive capabilities to control it. For example in an unstructured environment it often happens that the robot does not know or does not recognize the place where the piece should be put (EO 6). Thus the position along the X axis and Y axis (see Figure 6) should be controlled by the human whereas the robot can compensate for the weight of the workpiece and control the orientation of the piece. Control allocations for SEO 6 and SEO 7 are shown in Figure 8.

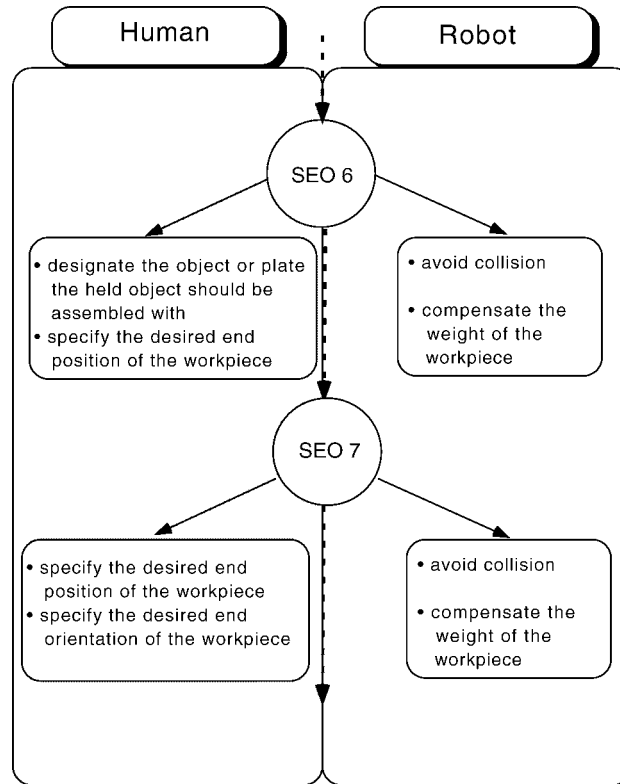


Figure 8. Function allocation according to the evolution of the task.

6. Implementation

In the preceding section we presented our concept for the dynamic shared control of a manipulator between the operator and the intelligent control system. In this section we show how to realize it. We first focus on the controller then on the transition recognition mechanism and also briefly on the safety factors.

6.1. COMPLIANT MOTION

For the distributed control of the 6 degrees of freedom of the manipulator among the human and the robot we use a hybrid position-force controller represented on Figure 9 [21].

$[P, O]$ represents the internal states of the manipulator: the position (P_x, P_y, P_z) and the orientation (O_x, O_y, O_z) of the end-effector. $[F, T]$ represents the external state of the manipulator: The forces (F_x, F_y, F_z) and the torques (T_x, T_y, T_z) applied on the force/torque sensor attached on the end-effector. I_6 represents the 6-dimensional identity matrix whereas S represents the diagonal selection matrix. If a component of S is '0', the corresponding degree of freedom is controlled by the

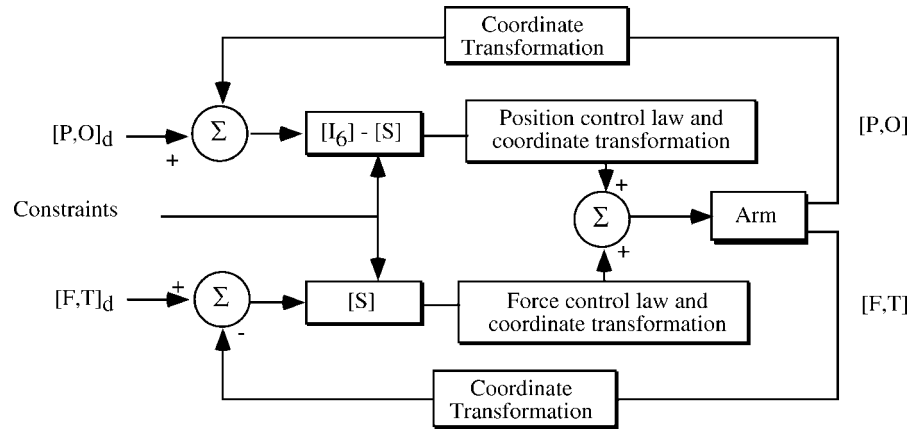


Figure 9. The hybrid position-force controller for a 6DOF.

ICS (Position control law), whereas if the component is '1', the degree of freedom is controlled by the human (force control law or compliant motion).

6.2. MODE TRANSITION

The cooperative work between human and robot requires not only the shared control of the different DOFs according to the situation, but also the ability to switch to the autonomous mode (Level A) or to the semi-autonomous mode (Level S) at the right time. This mode transition could be initiated whether by the ICS (automatic transition) or by the human (manual transition).

Automatic transition. The transition between the level A and S occurs automatically when an error has been detected during the execution of an EO or when the robot recognizes its incapacity to execute the EO because parameters are missing.

Manual transition. The transition between the level A and S can also be initiated manually when the operator applies the corresponding forces on the end-effector. All EOs are guarded motion, so that if the applied forces cross a given transition threshold, the transition is initiated.

The transition recognition makes use of rules and facts which tell the system how to react to a given situation. In our case the situation is determined by four different types of parameters:

1. The operation cycle status: it characterizes the elementary operation (EO or SEO) which is currently executed.
2. The operation status. It specifies if an error has been detected.
3. The task specification status. It specifies which parameters are missing for the autonomous execution of the task.
4. The sensor data. The sensors are force/torque sensors as well as position sensors (overhead camera or hand camera).

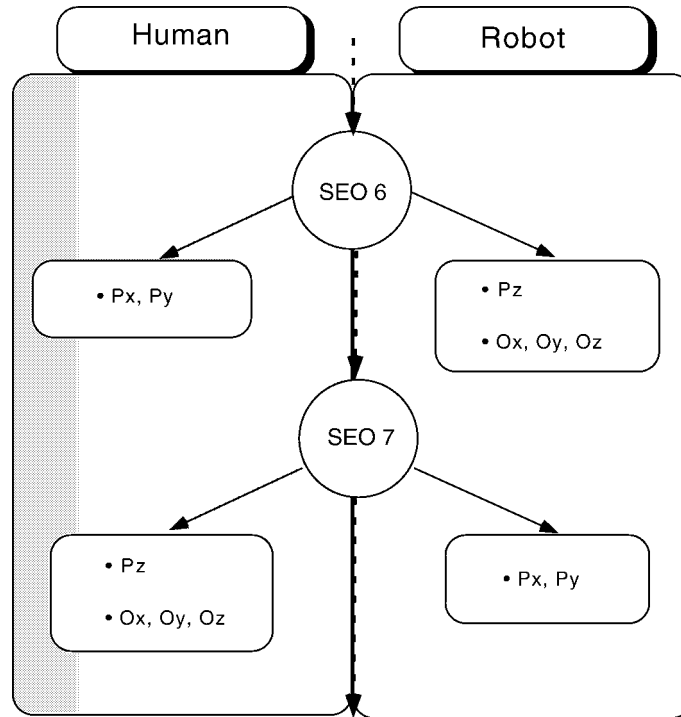


Figure 10. Control allocation of the degrees of freedom.

As an example we give the rule which activates the transition from the EO 6 to SEO 6.

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if((operation_cycle_status = EO6)
  and (
    (operation_status = error)
    or (operation_status = incomplete)
    or (Fx > Transition_Threshold_x)
    or (Fy > Transition_Threshold_y)))
then (transition = 1)

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6.3. SAFETY FACTORS

At the moment the safety of the operator cooperating with the robot is guaranteed by the following measures:

1. Speed: The execution speed of the manipulator is limited.
2. Guarded Motion: If the forces applied on the end-effector cross a security threshold the task execution is interrupted.
3. Hardware solutions like bumpers or buttons in order to stop the robot immediately in an emergency situation.

7. Results and Discussion

Our concept was implemented and tested on the robot system KAMRO (Karlsruhe Autonomous Mobile Robot). The robot consists of a mobile platform with an omnidirectional drive system using MECANUM wheels and two PUMA manipulators with 6 degrees of freedom mounted in a hanging configuration. Besides the robot is equipped with a multitude of sensors: 1 over-head camera, 2 hand-cameras, force/torque sensors on each manipulator and ultrasonic sensors on the mobile platform.

We present the results obtained for SEO 5 – 7 with our robot KAMRO. The evolution of the forces applied by the human on the end-effector as well as its position are presented in Figure 11. During the first phase (SEO 5) P_x and P_y are controlled by the ICS and are quite regular, whereas P_z is controlled by the human. The transition to SEO 6 is initiated manually. The transition threshold is crossed over at $t = 4,5$ s. The manual transition allows the human to specify the transfer height which is controlled by the ICS during the next SEO (SEO 6).

The advantages of our approach are the following:

- The error recovery occurs on-line.
- The operator interacts directly with the robot. This is a very natural communication way which renders the task easier for the human.
- Through direct interaction the human keeps a direct force and visual feed back from the working environment and can better exploit his very good sensing and actuating capabilities.
- The control of the DOF of the manipulator is shared dynamically between the robot and the human. The right mixture of robot autonomy and human interaction is adapted to the state of the task execution.
- The human activates the transitions between two different operations executed by the robot. So the robot has to adapt himself to the working rhythm of the human.

8. Conclusion

In this paper we outline the problems of autonomous robots for executing a complex task in unstructured environments. A possible compromise to overcome these limitations is to find the right balance between robot autonomy and human-robot interaction. We present a method which integrates the human-robot interaction in the task plan and allows a dynamic mixture of human and robot capabilities according to the state of the task execution. The combination of the capabilities occurs through an hybrid position-force controller which supports physical interaction between human and robot. This kind of communication presents the advantage that it is intuitive and allows to exploit optimally the very good perception capabilities of the operator.

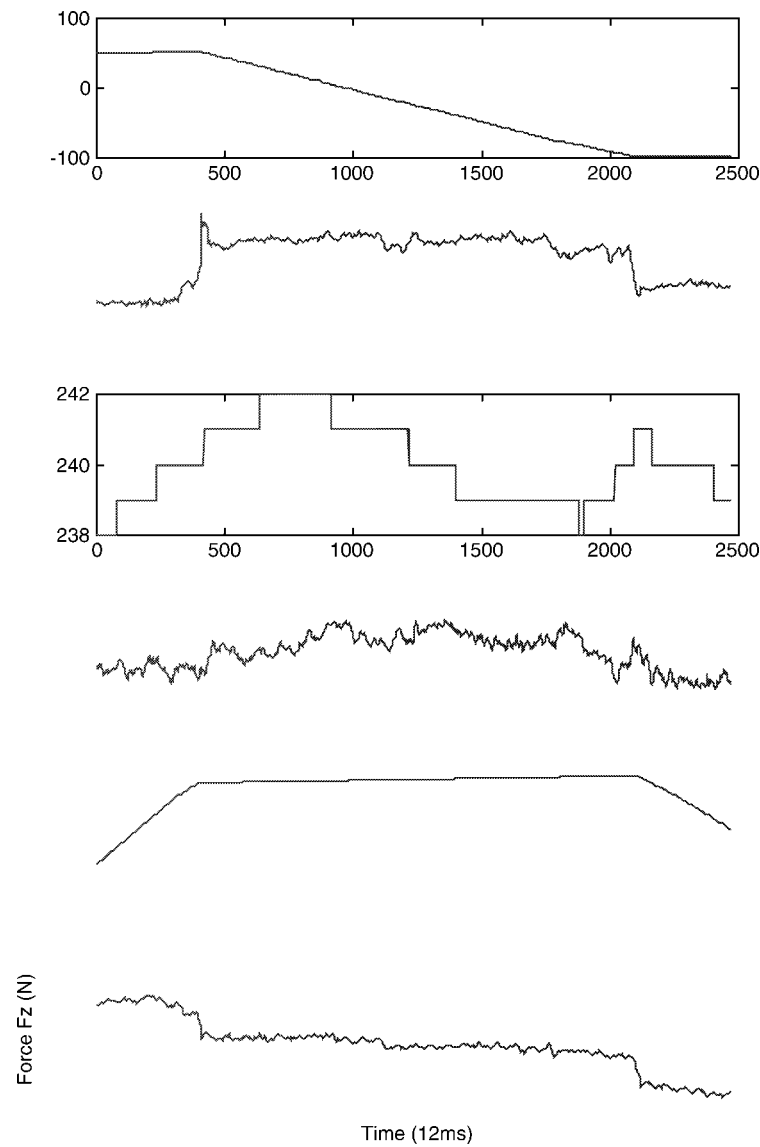


Figure 11. Position and Forces applied on a manipulator's end-effector as a time function.

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