Sharing and Trading in a Human-Robot System

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1. Introduction

With the functions of physical robots now extended beyond academia into factories, homes and fields, the interactions between humans and robots have become increasingly extensive and ubiquitous (Haegele et al. 2001). The current state of human interaction with robots in comparison to simple "machines" that operate in structured environment, such as manufacturing automation, is quite different. Robots differ from simple machines in that they are mobile. Some may be autonomous and their actions are not predictable in advance. Hence, there is a need to look into different interaction roles between humans and robots. The issue of interaction roles is an emerging research area in robotics namely Human-Robot Interaction (HRI) (Murphy and Rogers 2001). HRI can be broadly defined as "the study of the humans, robots, and the ways they influence each other" (Fong et al. 2001b). To provide realistic experimental settings, researchers working in this area need to develop Human-Robot System (HRS) to facilitate the study of HRI (Murphy and Rogers 2001). Here, HRS is defined as a "mixed system in which both human and physical robot interact, each as a cooperative intelligent entity" (Hancock 1992).

In the context of HRI, an important concern is how human and robot cooperate in a HRS (Sheridan 1992; Murphy and Rogers 2001). In remote operation applications such as space explorations, military operations, automated security, search and rescue, etc., the human does not have direct visual awareness of the environment to perform the required tasks. In these applications, a tight interaction between the human and the robot is required for effective cooperation and coordination. This raises an interaction dilemma: on one hand the robot operating in the remote environment can be expected in a "better position" to advise/inform the human regarding navigation issues (i.e. react locally to the remote environment) and refuses consent to dangerous human commands (e.g. running into obstacles); on the other hand, due to its limited ontologies, the robot requires human assistance on tasks such as object recognition, decision-making, and so forth. Here, limited ontology means that the robot is not able to use constraints either from its knowledge-base or from the environment to control its unspecified parameters.

To overcome the above dilemma, adapting to appropriate roles that exploit the capabilities of both human and robot as well as crafting natural and effective modes of interaction are important to create a cooperative HRS. To this end, innovative paradigms have been proposed over the years to redefine the roles of human and robot from the traditional master-slave relationship (Hancock 1992; Sheridan 1992), such as to model the human as cooperator (e.g. Lee 1993; Bourhis and Agostini 1998; Fong et al. 2001b; Hoppenot and Colle 2002; Bruemmer 2003) rather than just as the master controller of the robot. On the other hand, the slave robot is modelled in such a way that it becomes an active assistant

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(e.g. Bourhis and Agostini 1998; Hoppenot and Colle 2002) or partner (e.g. Fong et al. 2001b; Lee 1993; Bruemmer 2003) of the human, supporting perception and cooperative task execution. To design a cooperative HRS based on the above paradigms, a basic research issue is to consider how to achieve cooperation via appropriate degrees of sharing and trading between human and robot which constitutes the main focus of this paper.

1.1 Definition of Sharing and Trading

It might be useful to first provide a working definition of sharing and trading as a basis for further discussion. In Webster's dictionary (Agnes 2003), "sharing" and "trading" are defined as: "to join with another or others in use of some (thing)" and "to exchange one (thing) for another" respectively. Here, "to join" means that both the human and the robot work together through the use of some "thing" to ensure the success of task performance; and "to exchange" means that both the human and robot give and receive an equivalent of "thing" which they own while working together. In the context of sharing and trading, the tasks are the actions both the human and robot undertakes to achieve their goals. Human, needs to be able to see those tasks, adjust them and add to them if necessary during sharing and trading. On the other hand, the robot needs to be equipped with the capability to scale its own degree of autonomy to meet with whatever level of input from the human. To facilitate this, both human and robot must adopt the same ontologies so as to prevent miscommunication when they share and trade.

1.2 Why Sharing and Trading?

Within the discipline of robotics, the concept of sharing and trading is widely used for incorporating the strengths of human and robot. The aim is to achieve mutual compensation of both the human's and the robot's individual weakness (Sheridan 1992; Hirzinger 1993; Lee 1993; Bourhis and Agostini 1998;; Fong et al. 2001b; Hoppenot and Colle 2002; Bruemmer 2003).
For instance, sharing of control and sharing of autonomy has often been described in both the literature of telemanipulation (Sheridan 1992; Hirzinger 1993; Lee 1993) and teleoperation of mobile robot (Bourhis and Agostini 1998; Fong et al. 2001b; Hoppenot and Colle 2002; Bruemmer 2003). In telemanipulation, an example of sharing is the manipulation of a task where the compliance control is done by the robot automatically while position control is achieved by human's manual control (Hirzinger 1993; Lee 1993). In mobile robot teleoperation, an example of sharing of control is described as follows: the human directly controls the robot on board pan-tilt-zoom camera to provide a movement direction, i.e. to provide perceptual guidance; and the robot will respond to the human command by scaling its autonomy to drive the mobile platform according in the direction of the gaze (Hoppenot and Colle 2002). In both cases, trading is normally used in conjunction with sharing to let human and robot assist each other via the exchange of control and task information when both have problem performing the assigned task (Sheridan 1992; Lee 1993; Kortenkamp et al. 1997; Bourhis and Agostini 1998; Fong et al. 2001b; Bruemmer 2003).
The basic questions in sharing and trading are as follows (Sheridan 1992): In sharing – "Which tasks should be assigned to human and which to the robot?" In trading – "Which aspects of the tasks to trade, and when should control be handed over and when should it resume control during task execution?" As a consequence, researchers from the domains

of telemanipulation (e.g. Hirzinger 1993; Lee 1993) and mobile robot teleoperation (e.g. Bourhis and Agostini 1998; Fong et al. 2001b; Bruemmer 2003) have developed various novel robotics control architectures to address these questions. Although their solutions are application specific, the fundamental principles are similar, that is, to facilitate interactive task allocation and cooperative decision-making between human and robot. The purpose of interactive task allocation is to spatially/temporally distribute the task to the human and/or robot, based on their intellectual capabilities and performance during task execution. The purpose of cooperative decision-making is to provide for arbitration/fusion of task commands from the human and the robot.

Although the concept of sharing and trading has been widely adopted and studied, it is far from fully developed. This is due to the progressive introduction of more intelligent and autonomous robots equipped with powerful and versatile mechanisms for interacting with humans.

The nature of the above problems provides a wide range of "interaction" space to consider how human and robot might share and trade to achieve cooperation. In particular, it is important to address the role of sharing and trading in accordance to humans' interacting with current state of autonomous robots. To understand how human and robot share and trade in a HRS, it is important to first identify the basic requirements which constitute sharing and trading. The aim is to present the classifications in a framework to assist in the design and development of a cooperative HRS.

This paper is structured as follows. Section 2 discusses the current HRS and what essential requirements constitute in the design and development of a HRS. The purpose is to serve as a basis for the discussion of sharing and trading in the following sections. Based on the concept of task allocation, Section 3 describes the concept of sharing and trading in designing HRS. Here, sharing and trading are eminent to explain the cooperation between human and robot. Subsequently, to illustrate the concept of sharing and trading on the design and development of a HRS, a case study is presented in Section 4.

2. Human-Robot System

Current HRS takes many forms. This can range from manually controlled system, such as teleoperation (Sheridan 1992) to autonomous robotics system that employ artificial intelligence, machine perception, and advanced control (Giralt et al. 1993). A simple illustration of this spectrum is presented in Table 1.

Six types of HRS and their applications are depicted in Table 1, presented in order of increasing robot autonomy/intelligence. Type 1 represents traditional master-slave teleoperation system. Type 2 represents teleoperation system that employs video technology, computer technology and force feedback. This facilitates a finer-gain of control (as compared to Type 1) for performing more complex/intrinsic tasks. Type 3 represents an advanced form of teleoperation, called telerobotics. As compared to Type 1 and 2, the robot is not directly teleoperated throughout the whole work cycles, but can operate in autonomous or semi-autonomous modes depending on the situation context. Type 4 is another form of Type 3 configuration with an important difference: the human located on the robot mobile base (e.g. the wheelchair), has direct visual awareness of the robot environment. Type 5 represents a highly autonomous and intelligent robotics system that has the capability to work cooperatively with humans. Finally, Type 6 represents fully autonomous robotic system that can operate without any human guidance and control.

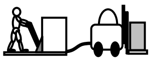
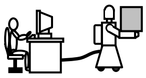
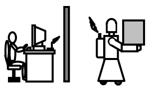
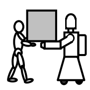
Human-Robot System	Descriptions	Possible Applications
Type 1: Teleoperation System (not computer-aided) 	The human is located remotely from the robot via the use of electric cable. However, the robot is directly controlled by human supervisor's own visual senses (line of sight). The robot extends the human's manipulation capability to a remote location so that he can work safely from the hazardous environment.	Underwater cleaning of reactor vessels, pipe inspection, etc. in nuclear power industry (Roman 1993).
Type 2: Teleoperation System (computer-aided) 	An extension of Type 1, but the human controls the robot through artificial sensing, computer, and displays. The robot extends both the human sensing and manipulation capabilities.	Robotics Surgery (e.g. the Da Vinci™ Surgical System, Thieme 2002), underwater operation (Roman 1993), etc.
Type 3: Telerobotics System (an advance form of teleoperation system) 	An extension of Type 2, but the human and the robot are separated by a barrier (environment, distance, time, etc.) that prevents direct interaction. The robot is normally equipped with high level of intelligence (such as safe navigation, path planning, etc.) while receiving higher-level instructions from the human instead of exercising continuous manual control as in Type 1 and 2.	Space exploration (Pedersen 2003), military operation (Gage 1995), automated security (Gage and Hower 1994), search and rescue (Casper and Murphy 2003), etc.
Type 4: Intelligent Mobility System 	A variant of Type 3, but the human and the robot are located closed together.	Rehabilitation, such as intelligent wheelchair (Bourhis and Agostini 1998) or mobility support system (Wasson and Gunderson 2001)
Type 5: Work Partner 	Robot is equipped with powerful and versatile mechanisms to communicate, interact and cooperate with human in a natural and intuitive way.	Robot as work assistants in factories, caretaker in home, etc. (Haegele et al. 2001)
Type 6: Autonomous Robot 	Robot replaces the human and performs the desired tasks autonomously.	iRobot Roomba Intelligent vacuum cleaner, tour guide, etc. (Burgard 1998)

Table 1. Different types of Human-Robot Systems

To deploy robotics technology effectively in a HRS, it is necessary to have a thorough understanding of the work environment and the tasks to be performed by the robot as well as to understand the nature of interactions between the human and the robotics system. Depending on the application settings, the work environment can be designed and engineered to facilitate the interactions between human and robot. For example, in the

application of surgery (Thieme 2002), both the human and robot perform the tasks in a structured environment. On the other hand, in planetary surface explorations (Pedersen 2003), the work environment is unstructured (i.e. partially or entirely unknown beforehand). In unstructured environments, it is not feasible to preprogram the tasks of the robot because the environment is only known after the actual execution of the task (Giralt et al. 1993). This poses a great difficulty to the interactions between human and robot when performing the task.
Here, in order to facilitate HRI, the following requirements are considered:

- - *Methods of Control:* This determines how the robot is being commanded and controlled in a HRS from the perspective of human interacting with the robot (Sheridan 1992; Murphy and Rogers 2001). This is discussed in Section 2.1.
- Robot Autonomy: This determines the required degree of robot autonomy in a HRS from the perspective of robot interacting with the human (Jackson et al. 1991; Giralt et al. 1993). This consideration is directly related to the degree of human intervention (i.e. degree of control) required for the robot to perform a desired task. This is discussed in Section 2.2.
- Human-Robot Communication: This determines how human and robot communicate (Zhai and Milgram 1992; Klingspor et al. 1997; Fong et al 2001b; Green and Eklundh 2003). This consideration is discussed in Section 2.3.

2.1 Methods of Control

The roles of human in a HRS are application-specific (Sheridan 1992; Murphy and Rogers 2001). For example, the use of human's adaptive characteristics as a controller has a long history of providing a cost-effective method of increasing system reliability. The key question, over the last few decades, has been the role of human in the control of a system. Should he be an active, serial element in the control loop or should he be a supervisor monitoring the progress of the system (Curry and Ephrath 1976)? As a human is a necessary system element in the control loop, effective control method is important to determine how the human and robot interact to increase the system performance. HRI practitioners and researchers normally adopt certain models to guide the development of the system.
Their modelling approach can be described by certain metaphors that characterise the roles of humans and that of the robots in the system. All of these models are important, since each stresses a different aspect of HRI. An understanding of the nature of interactions of these models can lead to the identification and classification of different control methods. The roles and relationships of human and robot in the different types of HRS depicted in Table 1 are classified in Table 2.
In Table 2, between the extremes of master-slave relationship to that of a fully autonomous robot, there is a spectrum of control options involving humans as supervisors, partners and teachers of the robots. This is because, rather than wait for the results of research in achieving fully competent and autonomous intelligent systems, one way is to make use of the semi-autonomous control schemes (Sheridan 1992; Giralt et al. 1993) for humans to assist robots and to some extent robots to assist human (Bourhis and Agostini 1998; Fong 2001; Wasson and Gunderson 2001). The term "Semi-Autonomous Control" normally refers to an autonomous robot which can interact intelligently with a human, who might command, modify, or override its behaviour (Sheridan 1992; Giralt et al. 1993).

Classification of Roles and Relationships	Descriptions
Master-Slave (*Type 1 and 2*)	This describes the traditional teleoperation system (Sheridan 1992). The master-slave operation is the most basic form of control, where the human must always remain continuously in the control loop. The operating principle is simple; that is, human (master) has full control of the robot (slave), e.g. all the control decisions will depend on the human. When human stops, control stops.
Supervisor-Subordinate (*Type 3 and 4*)	Here, the robot does not simply mimic the human's movements as in the Master-Slave role. Instead, the worker robot has the capability to plan and execute all the necessary intermediate steps, taking into account all events and situations with minimum human intervention. On the other hand, the human as a supervisor divides a problem into a sequence of tasks, which the robot performs on its own (Sheridan 1992). If a problem occurs, the human supervisor is responsible for finding a solution and devising a new task plan.
Partner-Partner (*Type 3-5*)	Here, robot is viewed as the human's work partner and is able to work interactively with the human. Both the human and robot are able to take advantage of each other skills and to benefit from each other's advice and expertise (Bourhis and Agostini 1998; Fong 2001; Wasson and Gunderson 2001). As compared to the Supervisor-Subordinate, if a problem occurs, the robot may provide the necessary assistance to find a solution (Fong 2001).
Teacher-Learner (*Type 3-6*)	This assigns the human a primary role of teacher or demonstrator and assumes that the learning robot possesses sufficient intelligence to learn from him (Nicolescu and Mataric 2001). Once the robot is able to handle the task, it can replace the human completely or work together with the human depending on the context of the application.
Fully Autonomous (*Type 6*)	Here, the aim is to develop robotics system that has the capabilities to operate without any human intervention once the control is delegated to the robot (Giralt et al. 1993; Burgard 1998). This implies that the human can only monitor but not influence the robot operation. The only intervention is to stop the robot operation when a potentially serious error occurs.

Table 2. Different roles and relationships of human and robot

2.1.1 Semi-Autonomous Control

The solution for the concept of semi-autonomous control comes from two main stems (Murphy and Rogers 1996): the teleoperation concept (Sheridan 1992) and the autonomous robot concept (Giralt et al. 1993). According to Giralt et al. (1993), in the teleoperation concept, both human and machine interacts at the human operator station level. On the other hand, in the autonomous robot concept, the focus is to have on-board, in-built intelligence at machine level so that the robot can adapt its actions autonomously to the task conditions during HRI. Although the semi-autonomous control concept may emerge from the two mentioned stems, the basic objective remains the same. That is, in order to advance beyond simple human control of a robot there is a need to provide the robot basic competence and degree of autonomy (see Section 2.2). This leads to a reduction in the degree of supervision by the human (Sheridan 1992; Giralt et al. 1993).

Based on the roles and relationships shown in Table 2, Fig. 1 presents a hardware framework to illustrate the nature of the interactions between human and robot under different control modes in performing a task. The human cannot perform the task directly, but must perform the task via two main interaction loops. One loop defines the interaction between the human and the robot via an interface. The second loop defines the interaction between the robot and the task via its sensors and actuators. The "intermediary" that facilitates the interaction between these two loops is the control mode. Here, each control mode is viewed as a "task interaction mode" for human to interact with the robot in performing a task. Fig. 1(a) represents traditional master-slave manual control system (Type 1). Fig. 1 (b) represents indirect (i.e. with computer-aided) master-slave manual control system (Type 2). Fig. 1(f) represents autonomous control for fully autonomous robot (Type 6). Fig. 1(c) to 1(d) represents semi-autonomous control system (Type 3-5).

Semi-autonomous control can be further classified into parallel type, serial type or a combination of both parallel and serial types (Yoerger and Slotine 1987). In parallel type (Fig. 1(c)), both manual control and autonomous control operate at the same time. The parallel type is normally referred to as Shared Control, an approach to incorporate the strength of the human and robot by letting them control different aspects of the system simultaneously in situations that required teamwork (Arkin 1991; Papanikolopoulos and Khosla 1992; Sheridan 1992; Hirzinger 1993; Lee 1993; Krotkov et al. 1996; Bourhis and Agostini 1998; Fong et al. 2001a; Wasson and Gunderson 2001; Hoppenot and Colle 2002; Bruemmer et al. 2003). It is normally used in situations where the task is too difficult to be achieved by either the human (via manual control) or the robot (via autonomous control) alone.

Shared control has been studied in different forms in both the domain of telemanipulation and teleoperation of mobile robot. The examples include position-compliance control (Hirzinger 1993; Lee 1993), vision-based perceptual guidance control (Papanikolopoulos and Khosla 1992; Hoppenot and Colle 2002), safeguarding control (Krotkov et al. 1996; Fong et al. 2001a; Wasson and Gunderson 2001) and behavioural control (Arkin 1991; Bourhis and Agostini 1998; Bruemmer et al. 2003).

In one way or another, all approaches have been based upon some form of coordination/fusion strategy with respect to the human inputs and the robot own assessment of the environmental task. As compared to manual control, shared control frees the human's attention from directly controlling nominal activities while allowing direct control during more perceptually intensive activities such as manipulation of parts (e.g. Hirzinger 1993; Lee 1993) and navigation in cluttered area (e.g. Bourhis and Agostini 1998; Bruemmer et al. 2003).

In serial type (Fig. 1(d)), either manual control or autonomous control can be selected as the operating mode at any one time. The serial type is normally referred to as Traded Control, a mutually exclusive approach for human and robot to exchange control on some basis (Papanikolopoulos and Khosla 1992; Sheridan 1992; Lee 1993; Kortenkamp 1997;

Bourhis and Agostini 1998; Bruemmer et al. 2003). The human and the robot can exchange control based on the demand of the task and the constraints of the environment due to goal derivations, addition/deletion of goals, modifications to the importance of goals/constraints, task completion, incompetence in performing the task and to veto dangerous commands/actions.

Basically, there are two perspectives on how control can be traded between human and robot in this context. In performing a navigation task (Bourhis and Agostini 1998; Bruemmer et al. 2003), the human may intervene and take the control from the robot (e.g. to give a new movement direction) if it moves in the wrong direction. On the other hand, the robot may override undesired commands (e.g. decelerates or stops) from the human, if the commands issue by the human may cause damage to itself. From this perspective, this control mode may allow both human and robot to "assist" each other in a partner-partner like manner.

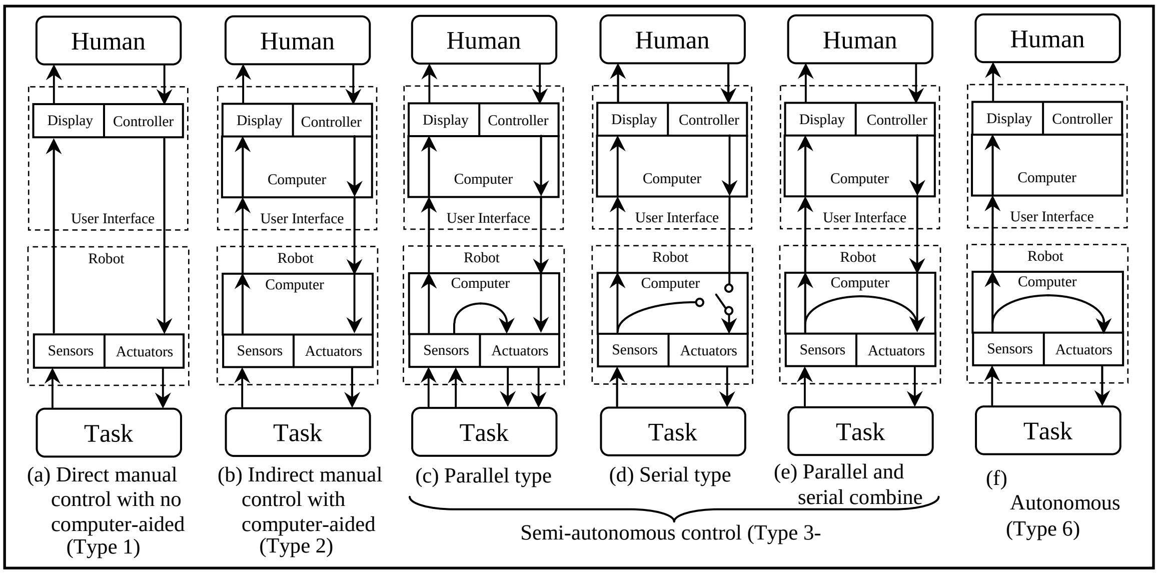


Figure 1. A spectrum of control modes ((Fig. (a), (b), (e) & (f) are adapted and modified from Sheridan (1992) and (Fig. (c) & (d)) are adapted and modified from Yasuyoshi et al. (1993))

In the combined configuration (Fig. 1(e)), both serial and parallel types interact to an extent, where the subtasks within each mode may also be shared and traded (Sheridan 1992). A classical example is the sharing and trading of control in the aircraft autopilot system (Billings 1997). During the cruise phase, in order to engage the autopilot system, the pilot trades the control over to the controller.

While the autopilot system holds the altitude, the pilot may adjust the heading, thereby sharing control at the same time. A classical example of the combine type is the Supervisory Control (SC) based on the Supervisor-Subordinate role by Sheridan (1992). Another recent example is the Collaborative Control (CC), an extension of SC based on the Partner-Partner model by Fong (2001) for the teleoperation of mobile robot. According to Fong (2001), the essential difference between CC and SC; is it can adjust its method of operation based on situational needs so as to enable "fine-grained sharing and trading of control". Specifically, in a situation where the robot does not know what to do or is performing poorly, it has the option to give control (e.g., for decision making) to the human in that situation. In other words, CC may enable work to be dynamically allocated to the robot or the human throughout the task performance. A summary of the different types of control discussed above is presented in Fig. 2.

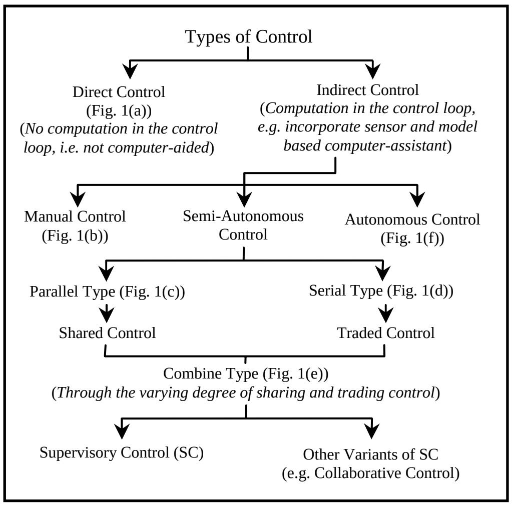


Figure 2. A classification of different types of control in a Human-Robot System

2.1.2 Control Modes

To facilitate varying degree of sharing and trading of control in a HRS, an approach is to develop a control architecture that provide a fine range of control modes (i.e. from the continuum of manual control to autonomous control presented in Fig. 1) for the human to interact with the robot. The purpose of each control modes can be viewed as a strategy to realise particular operations (i.e. basic actions).

Adoption of a certain control strategy is required for adequate interaction and appropriate intervention. A control strategy can range from using abstract goal-oriented commands (i.e. high-level commands) to detail descriptions of the task. The choice of which control strategy to use is related to the type of communication format used (see Section 2.3.2), communication bandwidth available (see Section 2.3.3) and the complexity of the task. One reason for using abstract goal-oriented control strategy is to reduce the communication content in situations when the communication delay is high. Here, task is specified in a sufficiently high-level form (i.e. in terms of goals and constraints) where the robot performs the task on its own without constantly requesting guidance/assistance. Examples of high-level abstract goal-oriented commands are: follow the target, grasp the target, etc.

Clearly, to perform the task specified in this manner, the robot must have the required autonomy (see Section 2.2) to respond to unseen circumstances. In complex task, detailed descriptions of the task can be specified in a hierarchy manner based on the desired goal, e.g. by describing the robot direction, movement, traveling distance and so forth, in a stepwise manner.

Basically, most of the proposed control modes in the literature (e.g. Hirzinger 1993; Lee 1993; Kortenkamp et al. 1997; Bourhis and Agostini 1998; Bruemmer et al. 2003) have two important features: complementary and redundant. The control modes are complementary in order to let both the human and the robot contribute according to their expertise. The aim is to envisage a tighter cooperation, where the interactions are more mixed initiative to let both assist each other. On the other hand, the control modes are also redundant so as to provide more options for the human to develop strategies (i.e. via a sequences of control modes) to perform the task.

According to Callantine (1996), control modes have four basic characteristics: (1) Engagement Conditions – dictate when the mode will engage and encompass target values that must be set so the mode can attain and/or maintain them, and the modes that are currently in use; (2) Disengagement Conditions - that govern when the mode disengages. A mode may disengage when another mode is engaged, or when critical target value information no longer applies; (3) Operation Modifications – dictate the allowable modifications to operation that human or robot can make while the mode is engaged; (4) Control Properties – which include the specific set of parameters (e.g. speed, direction, etc.) that the mode controls, and the manner in which the mode controls them.

2.1.3 Control Mode Transitions

The characteristics of each control modes give rise to specific relationships between modes. Each control modes may have its own set of sub-modes, therefore the sub-modes of a given control modes can interact with the control modes of another. Hence, an important facet of control modes is mode transition. It determines when a particular control mode/sub-modes should be engaged or disengaged. According to Degani et al. (1995), a mode transition can result from three types of input: human initiated, robot initiated, or mixed initiated (i.e. from both human and robot).

An effective control mode transition will involve two important attributes, that is, monitoring and intervention.

Monitoring can be viewed as a precondition for intervention (Sheridan 1992). For example, once a task is delegated to the robot, the human must monitor the robot operation to obtain adequate feedback on its task performance so as to ensure that it is done properly. Adequate feedback can be achieved via observation to inspection, such as checking the robot agenda, reasoning, plan, etc. The observation can either be by direct viewing or mediated via a sensing device (see Section 2.3.1). If the robot encounters problems during execution, the human monitoring the situation will step in to update the commands or provide guidance to the robot. In cases where the errors cannot be recovered, the human may trade the control over, by stopping the operation and repairing the robot actions, e.g. via programming of new behaviours that are necessary to accomplish the task.

To classify the different levels of intervention, the three-level paradigm proposed by Rasmussen (1983), namely skill-based, rule-based and knowledge-based, is adopted. This paradigm is adopted because it is able to characterise both human and robot behaviours (Bourhis and Agostini 1998). For example, when a problem arises, the human or robot may simply use its sensory-motor actions (i.e. the skill-based behaviour) to react to the situation, or in known situation, standard operation/reaction procedure may be applied (i.e. the rule-based behaviour). On the other hand, if the situation is unknown to the human, he can use all his knowledge to evaluate the situation and make a decision from various goals (Sheridan 1992).

This can also be used to describe robot intervention behaviour. A good example is the application of remote operations where the robot situated at the remote environment is in a better position to give indication to the human if he executes the wrong commands (Bourhis and Agostini 1998; Fong et al. 2001b; Bruemmer et al. 2003). Another instance is the robot may trade the control over and execute autonomously in situation such as loss of communication.

Depending on the context of the situation, the intervention frequency can range from low to high. A problem in mode transition is the robot may not be able to keep up with the state of the world or of the task when the human intervenes and takes control over from the robot (i.e. during trading of control). This can make it difficult and dangerous for the

robot to resume its operation once the task is delegated back to the robot by the human. This is because the robot's model of the world and of the task is inconsistent with the real state of the world (Kortenkamp et al. 1999). In addition, it is also difficult to know when control should be handed over to the robot and when it should be taken back (Sheridan 1992). To overcome this, the human and the robot must share some knowledge of the robot activities during task execution (Jackson et al. 1991). The human must understand the behaviours and the intention of the robot, if he wants to intervene to modify/change the mode (Bruemmer et al. 2003).
On the other hand, the robot must have the knowledge to interpret the human commands so as to respond to the control mode changes (see Section 2.2). In addition it must constantly update its knowledge-base so as to keep up with the real state of the world (Kortenkamp et al. 1999). This implies that it is important for both human/robot to develop a model of the interaction process based upon readily available interaction cues from each other so as to prevent mode confusion. Mode confusion (Bredereke and Lankenau 2002) arises when the mental model of the human does not match the model of the robot during HRI.

2.2 Robot Autonomy

To respond to the range of control modes and facilitate mode transitions, the robot must have the required autonomy to interact with the human. Here, the term autonomy is defined as "the ability of an agent (in this case, a robot) to act efficiently without any human's intervention" (Braynov and Hexmoor 2002). By stating that a robot is autonomous, it does not mean that the robot is thoroughly self-governing and capable of completing self-planning and self-control. However it can operate with some known (to the human) level of capability in the absence of human supervision/management for a defined period of time (Jackson et al. 1991).
Robot autonomy encompasses two basic attributes (Giralt et al. 1993): operating autonomy and decisional autonomy. Operating autonomy refers to the basic operational capability (i.e. the technological considerations) of a physical robot. For instance, to be "operational", a mobile robot must be equipped with the following basic components: Adequate sensors for navigation (e.g. range sensors for obstacles avoidance, detection, and location sensors to determine its own location), communication transceivers to interface with the human interface via a communication link, embedded computation and program storage for local control systems (e.g. to interpret commands from the human interface and translate these into signals for actuation).
Decisional autonomy refers to the level of intelligence imbued in a robot. This includes an internal representation of the world and of the task, and the capabilities to act reasonably in an unstructured/semi-structured environment. This encompasses the ability to reason about its own action, learn, and adapt to some extent on the basis of human feedback or from its own environment over a given period of time.

2.2.1 Robot Autonomy versus Human Control Involvement

Fig. 3 presents another view of describing the control modes in Fig. 1. The basic idea is to set up a discrete scale of robot autonomy, which enables the human to interact with the robot with different degrees of human control involvement. The horizontal axis represents the degree of robot autonomy, while the vertical axis corresponds to the degree of human control involvement.

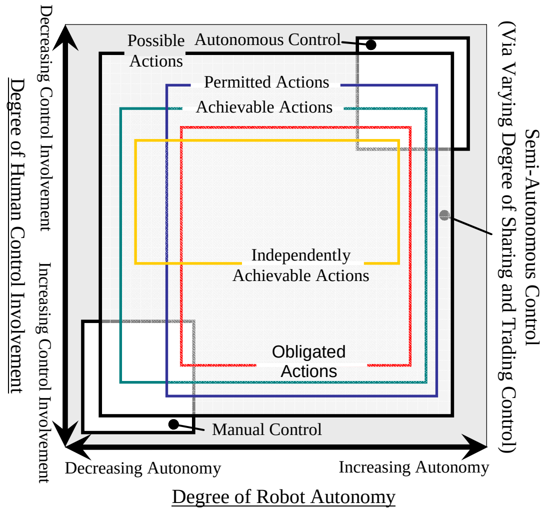


Figure 3. Control modes based on robot autonomy and human control involvement in accordance with varying nested ranges of action of robot

As shown in Fig. 3, the robot autonomy axis is inversely proportional to the human control involvement axis. Within these two axes, the manual control mode is situated at the bottom-left extreme, while the autonomous control mode is located at the top-right extreme. Between these two extremes is the continuum of semi-autonomous control. Within this continuum, varying degrees of sharing and trading control can be achieved based on varying nested ranges of action as proposed by Bradshaw et al. (2002a). They are: possible actions, independently achievable actions, achievable actions, permitted actions and obligated actions and are described in Table 3. Based on these five actions, constraints can be imposed so as to govern the robot autonomy within each level of control modes.

Ranges of Actions	**Descriptions**
Possible Actions	This refers to the theoretical maximum possible actions a robot can act with its given operating and decisional autonomy.
Independently Achievable Actions	This refers to a subset of possible actions that the robot could be expected to achieve independently with minimum human intervention.
Achievable Actions	This refers to a larger set of actions nested within the range of possible actions that could be achieved by the robot if it is able to work interactively with the human.
Permitted Actions	This refers to the actions nested within the range of possible actions that the robot is allowed to act (i.e. permitted by the human).
Obligated Actions	This refers to a subset of permitted actions that the robot is compelled to act.

Table 3. Degrees of autonomy based on varying nested ranges of action (adapted from Bradshaw et al. 2002a)

Another perspective of relating the degree of robot autonomy to human control is based on Sheridan's (1987) ten-level formulation of robot autonomy presented in Table 4. This formulation views the robot as a highly intelligent system that is capable of performing a whole task by itself in a given context. Here, the degree of robot autonomy is scaled accordingly based on human "decision" and "approval" when performing the task. Through this, a fine-grained presentation of a continuum of control between the robot and the human can be achieved.

Low ↑ Degree of Robot Autonomy ↓ High	1. Robot offers no assistance: the human perform the whole task	High ↑ Degree of Human Control ↓ Low
	2. Robot may assists by determining the multiple options of performing the task	
	3. Robot assists by narrowing down the options to a few, which human need not follow	
	4. Robot selects one action and the human may or may not approve	
	5. Robot selects action and implements it if the human approves	
	6. Robot informs and allows the human some time to veto task execution	
	7. Robot performs the task and necessarily informs the human what it did	
	8. Robot performs the task and informs the human what it did only if human explicitly requests	
	9. Robot performs the task and informs the human what it did, if it decides human should be informed	
	10. Robot does whole task autonomously	

Table 4. Ten-level formulation of robot autonomy (adapted from Sheridan 1987)

2.3. Human-Robot Communication

To ensure that the robot responds to the correct control mode when varying its own degree of autonomy, issues pertaining to Human-Robot Communication (HRC) is important. In Human-Human communication, humans communicate with each other easily through the same language. They can communicate effectively through electronic communication devices or face-to-face. However, in the case of HRC, it is not that straight forward, because the human cannot communicate with the robot directly. A well-defined communication channel is required to address the different modes of interactions between the human and the robot. Some of the basic considerations in HRC are: methods of communication, communication format, communication bandwidth and the purpose of communication as discussed in the following sections.

2.3.1. Methods of Communication

This relates to how information is transferred from the human to the robot (or vice versa). This issue is controversial because the current state of HRC encompasses a spectrum of methods, such as Personal Computer (PC) based control interfaces, Personal Digital Assistant (PDA) as interface devices (Fong et al. 2001b) and haptic interface which enables “drive-by-feel” (Fong et al. 2000) capability. In addition, methods such as speech and gesture (vision), that is analogous to human form of communication, are also widely used (Fong et al. 2000). The use of these methods is problem-specific or application-specific. However, regardless of the method used, effective communication exchange between the human and robot is paramount.

2.3.2 Communication Format

This pertains to the communication language used for information trading between the human and the robot. Zhai and Milgram (1992) proposed the notion of “continuous” and “discrete” languages as two different coding mechanisms to describe human-robot information trading.

According to Zhai and Milgram (1992), continuous language is used to represent information that is distributed continuously in quantitative or qualitative form, either along a spatial or a temporal dimension. In the context of robot communicating with human, examples include sending of raw sensors data, video images, etc. (i.e. perceived by the human).

In the context of human communicating with robot, examples include sending of continuous signal (e.g. via input devices such as joystick) to control the robot. On the other hand, discrete language is used to represent information which consists of separate or distinct elements.

Examples of discrete language are signs, symbols, written text, etc. used for communicating with the robot. As compared to continuous language, discrete language is normally used when the available information bandwidth is low or the communication delay is high. However, this implies that the robot must have sufficient autonomy (see Section 2.2) to perform the task.

A good example of using discrete language for HRC is through the use of dialog. The concept of using dialogue has recently received considerable research attention. Emerging from the research of mixed initiative artificial intelligent systems, it was subsequently adapted for HRC (e.g. Fong et al 2001b; Green and Eklundh 2003).

An example of dialogue adapted from (Green and Eklundh 2003) in defining a task during human intervention is as follows:

Human: Robot!
Robot: What is the task?
Human: Patrol Area A
Robot: Patrol Area A?
Human: Yes
Robot: Going to Area A

The idea of using dialogue is natural as it is very similar to human-human conversation. The purpose of confirming the human question (e.g. Patrol Area A?) is to ensure that the human has given the right command. If a wrong command is given, the human has a chance to correct his mistake. Using “confirmation” helps to prevent errors (i.e. giving wrong commands) and allows the robot to assist the human to learn from the mistake. Although this method is intuitive, it is difficult to decide how and when the robot should provide assistance or request for help. This issue is task specific and can only validate using human subject experiments.

2.3.3 Communication Bandwidth

This relates to the amount of HRC required to perform a given task. A good communication system is two-way (full duplex) with high data rate so that command data can be transferred from the human to the robot, and at the same time information of the robot can be conveyed back from the robot to the human.

The amount of communication can be quantified by the information quantity, measured in bits, and the information transfer bandwidth, measured in bits per second, of the messages that must be communicated between the human and the robot (Jackson et al. 1991). For instance, high communication bandwidth is normally required in manual control (such as teleoperation), because the human must control each movable function of the robot in real time. On the other hand, lower communication bandwidth is required in semi-autonomous control because continuous control of the robot is not required (see Section 2.1.1).

2.3.4 Purposes of Communication

This pertains to what type of information is shared and traded between human and robot during communication and what is the purpose of this information sharing and trading (Klingspor et al. 1997). In performing a task, the human must provide the robot with accurate information about the task to be performed.

On the other hand, the robot should communicate to the human any information regarding its state and provide a feedback of the current status of the task to allow him to evaluate the robot task's successes and faults. In addition, it is important for the robot to convey any difficulty its encounters during the task (therefore needs human's assistance). A simple illustration of information sharing and trading between a human and a robot in a fetch-and-carry task is conveyed in Fig. 4.

The types of information presented in Fig. 4 are classified as follows (Scholtz 2002): task information, environment information and robot state information. In the context of human communicating with the robot, task information is the knowledge of the task as specified and described by the human to be performed by the robot (Fig. 4(a) & (e)). Task information is shared between the human and robot as follows: in Fig. 4(a) and (e), the human performs a communicative act 'r' (e.g. via any one of the communication method introduced in Section 2.3.1), addressed to the robot.

Through this, the following information is accessible to the human and the robot: 'r' means task specification (in this case the object to be handled, its location and destination), which are necessary for the task execution. By describing the task, the human provides the necessary instructions to the robot, about how to specify the task. Hence, the task information specified by 'r' is shared.

In the context of robot communicating with the human, task information is the knowledge of the robot with respect to the overall task defined by the human during task execution. This includes the robot's knowledge of its current location, its destination (Fig. 4(b)) and its next task execution decision (Fig. 4(d)).

Environment information consists of information in the robot's working environment (Fig. 4(c)). Examples of environment information are the objects (static or dynamic) in the environment and the robot's location relative to these objects. Robot state information is the information pertained to robot's status (e.g. speed, sensors status, health, etc.) and configurations (e.g. maximum sensing distance, available behaviours, etc.). In Fig. 4(b) – (d), information is shared between the human and robot via monitoring the execution of the tasks by the robot. Fig. 4(f) presents a scenario where information is shared and traded between the human and the robot.

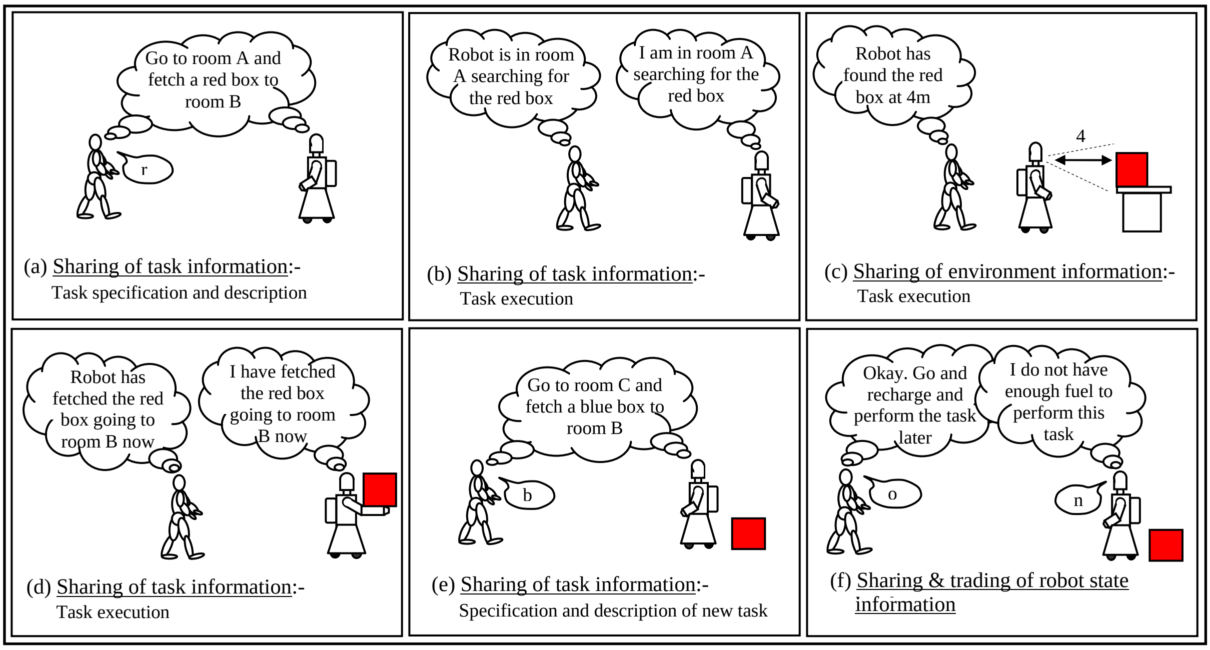


Figure 4. An illustration of information sharing and trading between a human and a robot in a fetch-and-carry task

In this scenario, the robot takes the initiative to inform the human about its problem by performing a communicative act 'n', and the human responds to this communicative act by performing a communicative act 'o'. Through this, the following information is exchanged between the robot and the human: 'n' means robot status (low fuel) and 'o' means "advises" (recharge and task specification). Hence, the meanings of 'r' (from the robot) and 'o' (from the human) is shared and traded. In fact, the robot may engage the human in communication at multiple task execution points to resolve differences in an entirely dialogue manner (see Section 2.3.2).

3. Towards Sharing and Trading in a Human-Robot System

It is proposed that a systematic approach to the design of a HRS can be based upon task allocation. That is "the assignment of various tasks either to humans or robots that are capable of doing those tasks" (Sheridan 1997). This perspective is based upon Fitts (1951) and is regarded by many as an essential component in systems engineering process (Sheridan 1997). In this quantitative approach, the attempt is made to identify which comparable capabilities are humans and machines "better at", and subsequently analyse (e.g. "matching") their best capabilities with aspects of the overall task at hand. This has come to be known as the "Fitts' Men-are-better-at - Machines-are-better-at (MABA-MABA) List". This list is often referred to as the first well-known basis for task allocation in the human factors literature (Hancock 1992; Sheridan 1997). Although this approach has gone though a sequence of different instantiations, e.g. published by Bekey (1970) and Meister (1982), the fundamental principle does not vary (Hancock 1992; Sheridan 1997). That is, the input for this approach is typically a list of abstract functions the HRS needs to achieve and the output is typically the same list categorised in terms of whether the human, robot, or some combination should implement the function (Hancock 1992; Sheridan 1997).

3.1 A Cooperative Human-Robot System

Although the MABA-MABA approach provides a formal and rational way for making allocation decisions, it has been criticised by many researchers (Hancock 1992; Sheridan 1997). The main concern is that there are large number of possible interactions between humans and robots for consideration, not simply just "human versus robots" (Bradshaw et al. 2002b; Hancock 1992; Jordan 1963; Sheridan 1997; Woods 2002). To develop a cooperative HRS, human and robot should be seen as the unit of concern rather than dichotomising them into separate unit (Jordan 1963; Hancock 1992; Sheridan 1997; Bradshaw et al. 2002b; Woods 2002). Jordan (1963) suggested that allocations of tasks between human and machines would only become useful if humans and robots were looked at as complementary, rather than comparable as in the MABA-MABA approach. He argued that this view is the key to optimise tasks allocation between human and robot. Sheridan (1989) shared the same view and stated that: "to cast the problem in terms of humans versus robots is simplistic, unproductive and self-defeating. We should be concerned with how they can cooperate". Bradshaw et al. (2002b) purport that the point is not to think so much about which tasks are best performed by humans and robots but rather how tasks can best be shared and traded by both humans and robots working together.

3.1.1 A Complementary View of Task Allocation

To provide a complementary view of how task can be allocated between human and robot, Woods (2002) proposed another perspective that does not concentrate on human shortcomings, called "Un-Fitts List". This is presented in Table 5 as summarised by Hoffman et al. (2002).

Robots			
Are constrained in that:		**Need Human to:**	
i	Sensitivity to context is low and is ontology-limited	i	Keep them aligned to context
ii	Sensitivity to change is low and recognition of anomaly is ontology-limited	ii	Keep them stable given the variability and change inherent in the world
iii	Adaptability to change is low and is ontology-limited	iii	Repair their ontologies
iv	They are not "aware" of the fact that the model of the world is itself in the world	iv	Keep the model aligned with the world
Humans			
Are not limited in that:		**Yet they create robots to:**	
v	Sensitivity to context is high and is knowledge- and attention-driven	v	Help them stay informed of ongoing events
vi	Sensitivity to change is high and is driven by the recognition of anomaly	vi	Help them align and repair their perceptions because they rely on mediated stimuli
vii	Adaptability to change is high and is goal driven	vii	Effect positive change following situation change
viii	They are aware of the fact that the model of the world is itself in the world	viii	Computationally instantiate their models of the world

Table 5. Woods' Un-Fitts List (adapted from Hoffman et al. 2002)