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Developing a Framework for Semi-Autonomous Control

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1. Introduction

Researchers and practitioners from the field of robotics and artificial intelligence (AI) have dedicated great effort to develop autonomous robotic system. The aim is to operate without any human assistance or intervention. In an unstructured and dynamic environment this is not readily achievable due to the high degree of complexity of perception and motion of the robots. For real-world applications, it is still desirable to have a human in the control loop for monitoring, detection of abnormalities and to intervene as necessary. In many critical operations full autonomy can be undesirable.

Such tasks require human attributes of perception (e.g. judgment), reasoning and control to ensure reliable operations. Although, robots do not possess the these human attributes, it is possible for the current-state-of robots to perform useful tasks and to provide appropriate assistance to the human to correct his control input errors by supporting perception and cooperative task execution. Systems which facilitate cooperation between robots and human are becoming a reality and are attracting increasing attention from researchers. In the context of human-robot cooperation (HRC), one of the research concerns is the design and development of flexible system architecture for incorporating their strengths based on their complementary capabilities and limitations. A well-known paradigm to facilitate such cooperation is that via the concept of semi-autonomy.

Although the concept of semi-autonomy is a widely adopted metaphor for developing human-robot system (HRS), there is no clear definition or agreement of how it should be represented. First, a formal representation of semi-autonomy is needed to identify and synthesise the key elements involved in the process of HRC. The purpose is to facilitate the development of a semi-autonomous control framework to seamless blend degree/level human control and robot autonomy at system-level. Second, there is a need to have a representation to address the role of semi-autonomy in decomposing and allocating tasks between humans and robots in a structured and systematic manner. This is essential in the initial design stage of HRS for providing a holistic basis of determining which system-level task should be performed by a human, by a robot or by a combination of both in accordance to their capabilities and limitations during task execution. A formalisation of semi-autonomy to address how task can be allocated between humans and robots is lacking in the current literature of robotics. This is because applications of semi-autonomy are normally

applied on an ad hoc basis, without a comprehensive formalism to address the problems of task allocation. Finally, without a formal representation, it is difficult to address, or discuss the research issues associated with the concept of semi-autonomy in a holistic manner.
Generally, the primary research issues of semi-autonomy can be summarised as follows:

i. When human-robot share control, there are apparent dependencies between the actions taken by them and the actions available to another as they can be operating competitively or cooperatively. In this case, their actions can reinforce or interfere with each other. Here, the main concern is how to resolve their conflicting actions dynamically during task execution.
ii. When human-robot exchange or trade control, either the human or robot has full control at any one time, and over time this control responsibility is switched between them in accordance to the task at hand. The next issue involved is: who decides when the control is to be transferred, and how to ensure the transfer of control is exchanged smoothly.
iii. The above issues consider parallel and serial control separately. This is useful as it simplifies the types of human-robot cooperation strategies, explicitly. If both parallel and serial controls are to be applied in conjunction, it can be unclear how these control strategies can assist in the design and development of a cooperative HRS. In particular, issues relating to the consequences, requirements and form of semi-autonomous control arise. A proposed HRS architecture must not only facilitate the combination of humans and robots actions, it must also allow for the arbitration of their actions.

The aim of this paper is to address the concerns above and the system design issues raised by the concept of semi-autonomy. This work emphasises the importance of modelling a framework of semi-autonomy as a foundation for the development of cooperative HRS. This includes a discussion of how the formulated framework can be applied for implementation of an HRS. The key idea of the development of the semi-autonomous control architecture is based on the different human-robot roles, namely Master-Slave, Supervisor-Subordinate, Partner-Partner, Teacher-Learner and Fully Autonomous mode by the robot. Finally, using the implemented HRS, proof-of-concept experiments are conducted to assess how semi-autonomous control is achieved at system-level. This has been implemented on a wide range of mobile robots including the iRobot ATRV-Jr and the Argo an amphibious all terrain, off-road vehicle.

2. Related literature

The research on semi-autonomy relates to many topics in the literature of robotics. This paper focuses on the exploitation of semi-autonomous control strategy to facilitate effective human-robot interaction (HRI) to increase task performance and reduce errors. Generally, research in this domain is widely known as supervisory control (Sheridan, 1992), collaborative control (Fong, 2001), mixed-initiative control (Bruemmer et al., 2003), adjustable autonomy (Kortenkamp et al., 2000), sliding scale autonomy (Desai & Yanco, 2005) and dynamic autonomy (Goodrich, 2007). In the context of semi-autonomous control, HRI practitioners and researchers normally adopt certain interaction paradigms for human delegation of control to the robotics system, where the control can be taken back or shared dynamically (i.e. sharing and trading of control) during operation (Ong, 2006). Their interaction paradigm can be characterized by the interaction roles and relationships between humans and the robots in an HRS. This section provides a background on the interaction roles that human and robot may play in an HRS. This is important in the design and development of semi-autonomous control architecture for HRI, because the human relationship with the robot can dictate the boundaries and constraints on the interactions between them. Subsequently, the idea of human-robot team (HRT) is introduced to differentiate the work here with other research work that also considers the use of different human-robot roles and relationships. This includes a discussion on the considerations of task allocation in developing a framework for semi-autonomous control, which is lacking in the literature of HRI.

2.1 Evolution of human-robot roles and relationships in robotics

2.1.1 Master-slave

According to Norman (2002), how human interacts with any technological system directly depends upon the human view of his relationship with that system. Historically, human normally recognizes himself as the *master* of the robot (Hancock, 1992). On the other hand, the robot is normally viewed as a *slave* of the human to service the needs and demands of the human. The history of modern robotics application based on this human-robot role and relationship began in the late 1940's, when the first *master-slave* telemanipulator system was developed in the Argonne National Laboratory for chemical and nuclear material handling (Vertut & Coiffet, 1985). With this system, the "slave" robot manipulator at the remote site reproduced exactly the motions imposed on the "master" handle by a human operator.

2.1.2 Supervisor-subordinate

With technological advancement comes robotic system of increasing capability, expanding the potential to facilitate and augment human work activities. It becomes critical to refine the roles and relationships that both human and robot can interact instead of just simply the "master-slave" relationship. In the late 1960's, many researchers and practitioners recognized this potential and started to consider how to improve the human relationship with the robot. Sheridan (1992) was one of the first to extend beyond the master-slave paradigm and formalized a new human-robot role and relationship called *supervisor-subordinate* relationship. This human-robot role and relationship is derived from the analogy between the human supervisor's interactions with human subordinates in a organization. A human supervisor gives directives that are understood and translated into detailed actions by human subordinates. In turn, human subordinates gather detailed information about results and present it in summary to the human supervisor, who must then infer and make decision for further actions. Sheridan stated that the human and the robot can also engage in such relationship but how "involved" the human supervisor becomes in the interaction process is determined by the autonomy of the subordinate robot. To date, the majority of research in robotics using this human-robot role and relationship has focused on telemanipulation for process control (Vertut & Coiffet, 1985) and also the teleoperation of mobile robots for space exploration (Pedersen et al., 2003), search and rescue (Casper & Murphy, 2003), military operation (Gage, 1985), automated security (Carroll et al., 2002).

2.1.3 Partner-partner

The master-slave and supervisor-subordinate relationship in HRS is hierarchical, with the human always acting as superior and the robot always subservient. In the early 1990s, researchers began to look into other human-robot role and relationship that is nonhierarchical, where the nature of interaction between the human and the robot is liken to a *partner-partner* relationship. One of the first to design an HRS (i.e. a telemanipulation system) based on this perspective is from Lee (1993). According to Lee, the robot should not be viewed as a slave or subordinate of the human, but rather as an active partner of the human. In particular, taking the full advantage of the robot capabilities to let the robot supports the human perception, action and intention. This was purported by Fong (2001) that to develop a cooperative HRS, the human and the robot should work as partners to exchange ideas, to ask questions, and to resolve differences just as in human-human interaction. He stated that: "*instead of the human always being completely in charge, the robot should be more equal and can treat the human as a limited source of planning and information*". To date, the *partner-partner* human-robot role and relationship is widely adopted in the area of rehabilitation to let the robot work as a partner of the human so as to provide appropriate assistance to him (Martens et al., 2001; Wasson & Gunderson, 2001). One example in rehabilitation is from Bourhis & Agostini (1998) that uses the *supervisor-subordinate* paradigm in which the human works cooperatively with a robotics wheelchair. As compared to partner-partner paradigm, the interaction between the human and the robot in supervisor-subordinate relationship is mutually exclusive where either human or robot can take control at any one time. In Bourhis & Agostini work, the cooperation between the human and the robot is based on the idea that both the human and the robot can be supervisor of each other for overriding each other actions.

2.1.4 Teacher-learner

Teaching a robot through a human teacher has been widely studied since 1970s (Shimon, 1999). For example, humans have performed the role of a teacher in the domain of robot manipulators. In this domain, the robot as a learner normally learns its trajectory either through a teach-pendant or direct guidance through a sequence of operations given by a human. With recent advances in the theory and practice of robotics, this approach has been extended to allow the robot learner to learn from the interaction at the human teacher's high level of abstraction (e.g. by demonstration (Nicolescu & Matarić, 2001)). Through this interaction the robot learns up to the point at which the robot is able to carry out complex task and request appropriate help when required. Currently, this human-robot role and relationship is widely used in HRI to *enhance* the interaction between the human and the robot. This is because researchers in HRI recognize that effective HRI not only requires technological intelligence of the robot but also a "knowledge" transfer between the human and the robot during operation, so as to let the robot learns more difficult or poorly defined tasks (Haegele et al., 2001).

2.1.5 Fully autonomous

Since the days of the Stanford cart and the SRI's Shakey in the early 1970's, the goal of building fully autonomous system has been what researchers in robotics have aspired to achieve (Arkin, 1998). To date, cleaning robots (e.g. intelligent vacuum cleaner) are among the first members of the autonomous robot family to reach the marketplace with practical and economical solutions (Fiorini & Prassler, 2000). In such HRS configuration, once the human has specified a goal for the robot to achieve (e.g. "Clean Area A"), the robot operates independently. As the robot performs the task, the primary role of the human is to monitor the robot's execution.

2.2 Human-robot team

Each of the five human-robot roles and relationships discussed in Section 2.1 is important, since each stresses a different aspect of the interactions between the human and the robot. It will be beneficial if the advantages of these five human-robot roles and relationships are considered in the design and development of a semi-autonomous robotics system. This implies that instead of using only one fixed role and relationship, multiple interaction roles and relationships are envisaged to let human and robot to work as a team. From the HRS design perspective, it is an advantage as it decomposes the HRI problem into smaller sub-problems. System designers can now concentrate on each specified HRI role and design the appropriate functions. As a result, this provides an interactive HRS development that is based on what the human and the robot are best suited under different task situations and different levels of system autonomy. This idea is analogous to a human-human team where each team member usually does not engage in a single role when they work together. Within a human-human team, they normally engage different roles based on their task skills and their changes in interaction roles to meet new and unexpected challenges (Chang, 1995).

The idea of getting a human and a robot to work as a team is not novel but the concept and implementation of multiple interaction roles and relationships and roles changing during operation is. The concept of Human-Robot Team (HRT) in the literature basically refers to human and robot adopting a partner-partner role and relationship described in Section 2.1.3. One notable exception is the work from Bruemmer et al. 2003. They explored the concept of HRT where each team member has the ability to assume initiative within a task. They state that to achieve this, both the human and the robot must have equal responsibility for performance of the task, but responsibility and authority for particular task elements shifts to the most appropriate member, be it the robot or the human. To facilitate, they suggested four roles for each member of a human-robot team, where either human or robot can take on the role of *supervisor* to direct the other team member to perform a high level task; *subordinate* role to perform high level task with less direct supervision by a supervisor; *equality of role* (i.e. partner), where each team member is wholly responsible for some aspect of the task; and as a subservient *tool* (i.e. slave), which performs a task with direct supervision by a supervisor.

The work by Bruemmer et al. (2003) is similar to the idea of HRT envisaged here, because both use multiple interaction roles and the need of role transitions. However, there are two differences. Firstly, the *type* of human-robot roles and relationships envisaged here not only considered human as supervisor and partner, it also considered human as master and teacher of a robot. Secondly, the work presented in this paper does not claim that the robot has the responsibility and authority to *direct* human in performing a task. In this work, human retains as the overall responsibilities of the outcome of the tasks undertaken by the robot and retains the authority corresponding with that responsibility even though the robot may be in the authority to guide certain aspect of the tasks (e.g. correct human control actions). This issue is discussed in Section 3.2.6.

In short, to achieve effective semi-autonomous control, the idea of HRT envisaged here requires both the human and the robot to engage in multiple interaction roles and role transitions during operation. The purpose is to let them perform different type of tasks and to meet new and unexpected challenges with the human maintained as the final authority over the robot. However, the HRS design considerations are no longer just on robotic development but rather on the complex interactive development in which both the human and the robot work as a cohesive team. To facilitate, one important consideration is the allocation of tasks between humans and robots in the initial design stage of an HRS. This is further discussed in the following section.

2.3 Task allocation

Issues pertaining to the task allocation between human and robot do not gain much attention in the domain of HRI. To date, research effort in HRI mostly concentrates on the development of HRS architectures and the incorporation of human-robot interfaces as means for human to control the robot (Burke et al .2004). The consideration of task allocation in HRI is normally done in an informal manner. HRI designers normally make allocation decisions implicitly based on the unique advantages possessed by both the human and the robot (i.e. based on the "who does what" mandatory allocation decisions). For example, prior knowledge of a task, "common sense" in reasoning and perception are attributes that are possessed by humans but not by robots. On the other hand, rapid computation, mechanical power, diverse sensory modalities and the ability to work in hazardous environment are great advantages of robots that humans do not possess (Sheridan, 1997). Although the informal allocation of task can be used to make allocation decisions reasonably well, it may not be able to provide a judicious provisional allocation decisions; i.e., looking into: *when* problem arises during task execution and *how* might human and robot cooperate to resolve the problem. Successful resolution of task allocations often requires not only an understanding of fundamental issues concerning the capabilities and limitations of humans and robots, but also of a number of subtle considerations when both human and robot interact in performing an assigned task. This view is based upon the literature from human factors engineering for Human-Machine Interaction (HMI) and Human-Computer Interaction (HCI) in automated system (Sheridan, 1997; Hancock, 1992); such as flying an airplane (Inagaki, 2003; Billings, 1997), supervising a flexible manufacturing system (Tahboub, 2001; Hwang, 1984) or monitoring a nuclear power plant (Sheridan, 1992; Hamel, 1984).
To illustrate, consider the following situations. In performing an HRS task, a human may get tired or bored after long hours of operations, or a robot may fail to perform an allocated task due to a lack of prior task knowledge or sensors malfunction. If any of these situations happen and the HRS is designed solely based on mandatory allocated decisions that do not anticipate any interaction strategies that allow human to exchange control with the robot, the overall HRS performance may degrade or the HRS may breakdown physically. This implies that such decisions are not efficient and efficacious under certain situations. A successful task allocation scheme for semi-autonomous control must also include considerations of *timeliness* and *pragmatism* of the situation for making provisional task allocation decisions (e.g. when a robot fails to perform its allocated task during operation, how does human assists the robot; or when the human has problem performing a task, how does the robot provides appropriate assistance to the human).

2.3.1 Concept of task sharing and trading

In the context of a HRT (Section 2.2), when reallocating tasks adaptively between human and robot, it is vital to know that dynamic HRI role adjustment comes at a cost. This is because it may interrupt the ongoing dynamic task process of human and/or robot. A major challenge is to ensure that the task interaction between human and robot is continuous and transparent so as to achieve seamless semi-autonomous control during task execution. As the task interaction between human and robot in an HRS may not be predictable and may occur in an arbitrary manner depending on the ongoing task performance and situation, it is not feasible to employ pre-programmed decision rules (e.g. as in adaptive task allocation for automated system (Hancock, 1992)) to trigger task reallocations dynamically based on pre-defined conditions. For successful accomplishment of a particular task in an HRS, both human and robot should cooperate through varying degree of human control, robot autonomy and appropriate human-robot communication when problem arises (Ong, 2006). This implies that task reallocation not only require to reallocate task responsibilities among human and robot (i.e. via role changing) but also to coordinate the interaction process between them. Examples include, resolve their conflicts, actions and intentions, arbitrate human/robot request for assistance, etc.

The decision to perform a task reallocation discussed above is invoked either by a human or a robot during task execution. By specifying task reallocation in this manner, the original definition of task reallocation based solely on the overall system task performance used in automated system may not be suitable (Sheridan, 1997; Hancock, 1992). Here, *task reallocation* is defined as the reallocation of a current desired input task that is allocated to the human and the robot with a completely new task specification. The conditions for task reallocation can be based on the ongoing task performance of the human and the robot, changes in task environmental or simply changes in the task plan that causes the current desired input task to be discarded. An approach useful for addressing this issue, i.e. making timeliness and pragmatic task allocation decisions is the concept of *task sharing and trading* proposed by Ong (2006). A human-robot cooperation concept that allows human and robot to work as a team by letting them contributes according to their degree/level of expertise in different task situations and demands. This concept not only considers how a robot might assist human but also how the human might assist the robot. Through this, a spectrum of cooperation strategies (Table 1) ranging from “no assistance provided to the human by the robot” to “no assistance provided to the robot by the human” can be envisaged to address contingencies that emerge when the human and the robot work together during task execution. Table 2 provides an abstract description of the prior task allocation in an HRS based on the considerations of capability of the performer but also on the timeliness and pragmatism of the situation. Consequently, this concept is adopted here for the formalization of the semi-autonomous control framework.

3. A framework for semi-autonomous control

Given Section 2.3.1, the interaction between a human and a robot in a semi-autonomous control system is in the context of a task. By *task* implies the required human’s and robot’s functions and the goals they are attempting to accomplish. This means that the “things” that the human and the robot can share and trade is placed within the context of a task. As posited by Ong (2006), the “things” that a human and a robot shared and traded is in the context of *human control*, *robot autonomy* and *information*, which constitute the key elements involved in the process of interactions between them. However, to consider how these elements constitute to the semi-autonomous control of a robot, there is a need to look into the basic activities within an HRS. This is further discussed in Section 3.1.

Human-Robot Cooperation Strategies	**Characteristics**
No assistance provided to human by robot.	This strategy is useful when human wants to perform a task by him/herself manually.
Robot assists human by extending his/her capability.	This strategy is useful to let the robot extends the human capability so that he/she can perform a task that is beyond his/her ability.
Robot assists human by dealing with different aspects of a task.	This strategy is useful to let the human and the robot cooperate to deal with mutually complementary parts of a task.
Robot assists human by providing appropriate support to the human.	This strategy is useful to let the robot provide active (i.e. constant or continuous) assistance to the human so as to reduce his/her burden or task demands.
Robot assists human by taking over the task from the human.	This strategy is useful to let the robot take over a task from the human when the human fails to perform a task or it can be the human who want the robot to perform the task by itself when he/she find that the robot has the ability to perform the task.
Human assists robot by providing appropriate support to the robot.	This strategy is useful to let human provide the require assistance to the robot when the human perceived that the task performance of the robot is not satisfactory or the robot request for human assistance.
Human assists robot by taking over the task from the robot.	This strategy is useful to let the human take over a task from the robot when the robot fails to perform the task.
No assistance provided to robot by human.	This strategy is useful to let the robot perform a task by itself with minimal or no human intervention.

Table 1. Different types of cooperation strategies between a human and a robot based on how the human and the robot might assist each other

Task Allocation	**Determine By**
Tasks that are best performed by the human.	“Who does what”
Tasks that require human-robot cooperation but may require the robot to assist the human.	Timeliness and pragmatism of the situation
Tasks that require human-robot cooperation but may require the human to assist the robot.	Timeliness and pragmatism of the situation
Tasks that are best performed by the robot.	“Who does what”

Table 2. A flexible prior task allocation based on “who does what” mandatory allocation and “when and how” provisional allocation decisions

3.1 Defining semi-autonomous control

According to Ong (2006), the basic task activities within an HRS may consist of:

- Desired task as input task, T_I
- Task allocated to the human, T_H
- Task allocated to the robot, T_R
- Task sharing and trading between the human and the robot, $T_{S\&T}$
- Task reallocation, T_{RE}

These basic activities may be related as shown in Fig. 1.

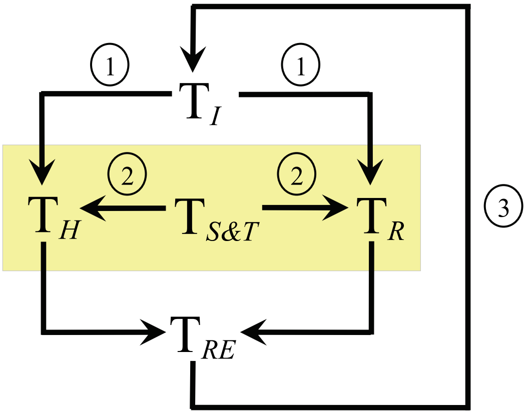


Figure 1: Activities within a Human-Robot System

In Fig. 1, it is suggested that there are three main paths to describe the activities within an HRS. The first path shown in Fig. 1 defines the input task (T_I) allocated to the human (T_H) and/or the robot (T_R). The second path defines task sharing and trading ($T_{S\&T}$) between the human and the robot. The third path represents task reallocation (T_{RE}) of the T_H and/or the T_R with a completely new T_I specification. Each of these five activities (i.e. T_I, T_H, T_R, $T_{S\&T}$ and T_{RE}) in Fig. 1 is further discussed in Section 3.1.1 to 3.1.5 respectively

3.1.1 Input task (T_I)

Given the task definition of a particular application task, such as large area surveillance, reconnaissance, objects transportation, objects manipulation, exploration of unknown environment, hazardous waste cleanup, to name a few. The next stage is to determine whether human, robot, or some combination of both should perform the T_I (i.e. prior task allocation) as follows. First, identify which tasks can *only* be allocated to either human (T_H, Section 3.1.2) or robot (T_R, Section 3.1.3) based on "who does what" mandatory allocation decisions. Subsequently, provisionally allocate tasks based on timeliness and pragmatic decisions, so as to take advantage of the symbiosis of the human and the robot capabilities to achieve task goals during task execution.

Generally, the considerations of making provisional task allocation based on the human and the robot capabilities can be characterised along several dimensions as follows:

- *Reasoning*: This includes attributes such as decision-making, task planning, situation understanding, and error detection and correction, to name a few. Consider an example of a robot performing a navigation task of traversing from one location to another location and get "trap" in the dead end environment causing the robot unable to reach the specified location. To let the robot perform this navigation task successfully requires human assistance such as decision-making and situation understanding to guide the robot out of this situation.

- *Perception*: This includes attributes such as multi-modalities sensing, object recognition/discrimination/classification, to name a few. Consider a situation in which a robot attempting to move into a room and encounters door curtains directly in its path. Depending on the robot sensors suite, the robot's perception system may have difficulty determining if the curtains are obstacles or whether its path is truly blocked. Thus, the robot may not be able to traverse into the room. However, if human perceives through the video feedback, from the robot's camera, that the obstacles are only curtains, he/she can assist the robot by overriding the robot's perception system and command the robot to drive through the door.
- *Mobility*: This includes attributes such as traverse distance, mission duration, repetitive/unique mission, consequence of failure, moving with minimal disturbance to environment, and complexity of working environment (e.g. distribution of targets/obstacles, accessibility (e.g. small spaces), slope variability, soil/surface consistency, degree of uncertainty, etc.), to name a few. For example, these attributes are important considerations when a human is delegating a navigation task to a robot or providing appropriate assistance to the robot when its encounter problems (as discussed above).
- *Manipulability*: This includes attributes such as object shapes (standard/unique), repetitive/unique motion, precision/dexterity motion, consequence of failure, moving with minimal disturbance, and complexity of motion, to name a few. For instance, these attributes are important considerations when a human is delegating a manipulation task to a robot or providing appropriate assistance to the robot when its encounter problems while performing the task.

The discussion above has provided an abstract view of T_I and attributes for making provisional task allocation decisions during task execution. This is essential because it provides a basis for describing T_H and T_R in Section 3.1.2 and 3.1.3 respectively.

3.1.2 Task of human (T_H)

The primary T_H in an HRS is to *control* a robot to perform particular application tasks. In general, this encompasses the following functions that the human might require to perform:

- *Decision-making* - to decide whether the robot has the ability to perform the desired task. The considerations for making this allocation decision can be based on task attributes discussed in Section 3.1.1. For example, to control a robot to perform a navigation/manipulation task, the human must first determine whether the robot has the "physical" functions or *operating autonomy (i.e.* the basic physical operational capability*)*, such as mobility/manipulability to execute the desired task. Next, if the robot has the required operating autonomy, the human must decide whether the robot has the required *decisional autonomy* (i.e. level of competence/ intelligence imbued in a robot) to carry out the task by itself. If the human decides that the robot has the required autonomy, then the human will proceed to task planning (discussed below). However, if the human determines that the robot does not have the required knowledge, he/she would need to imbue the robot with the necessary capabilities to perform the task

- *Task planning* - to schedule the task process and how it is carried out. For instance, setting goals, which the robot can comprehend.
- *Teaching* - to transfer task knowledge to the robot if the robot does not have the prior knowledge to perform the desired task.
- *Monitoring* - to ensure proper robot task execution and performance.
- *Intervention* - to provide appropriate assistance to the robot if any problems arise during task execution. Problems can include hardware failures, software failures, and human manual configuration requests for unscheduled support, to name a few.

The above are the conceivable tasks that can only be allocated to human based on the human roles in an HRS, e.g. as supervisor, partner or teacher of the robot as discussed in Section 2.1. The human roles in an HRS in turn determine how a robot might perform the HRS task. This is discussed below.

3.1.3 Task of robot (T_R)

The primary T_R in an HRS is to response to human control and in turn adapts its *autonomy* to perform the application tasks. Basically, this encompasses two basic functions that the robot requires to perform:

- *Physical task execution*: In general, how a robot might execute an HRS task depends on how human control the robot; i.e. based on the human-robot roles and relationships in an HRS as established in Section 2.1. For example, if the human adopts the master-slave paradigm to control the robot, then the robot will just mimic the human control actions exactly in performing the HRS task. On the other hand, if the human adopts the supervisor-subordinate paradigm to control the robot, then the robot will perform the HRS task planned by the human with minimum human intervention.
- *Feedback information*: To facilitate human monitoring and intervention of the robot task execution, the robot must feedback information to the human. This includes task information, environment information and the robot state information.

Section 3.1.2 and this section have provided an overview of T_H and T_R. This is essential because it provides a basis for describing the $T_{S\&T}$ between the human and the robot in the following section. Consequently, this will define the mode of operation for semi-autonomous control.

3.1.4 Task sharing and trading ($T_{S\&T}$) between human and robot

The concept of $T_{S\&T}$ (Ong 2006) introduced in Section 2.3.1 is based on how robot assists human – human assists robot (RAH-HAR). Within this paradigm, both the human and the robot may work as a team by engaging in different roles and relationships (Section 2.2) so as to exploit each other capabilities and/or compensate for the unique kinds of limitations of each other during task execution. Although the concept of $T_{S\&T}$ is able to describe the different types of cooperation strategies between a human and a robot based on how they might assist each other (as depicted in Table 1), it does not provide much insight into the design and development of a semi-autonomous control architecture given the interaction roles they might adopt during task execution. To facilitate, it is important to consider the dynamics of the $T_{S\&T}$ process so as to address the contingencies that arise when the human and the robot work together during task execution. To address, there is a need to characterise the underlying basic elements that constitute the $T_{S\&T}$ between the human and the robot.

A. Basic Elements of $T_{S\&T}$

Given the key elements namely *human control*, *robot autonomy* and *information* involved in the process of interaction between a human and a robot (Ong 2006); it is defined here that for semi-autonomous control of a robot, the human must select the right control mode to share and trade control with the robot. On the other hand, the robot must adapt the right degree of autonomy so as to respond to the selected control mode (i.e. sharing and trading its autonomy with the human). This implies that "human control" and "robot autonomy" are placed within the context of a task collaboration for the human and the robot to accomplish their respective goals. By *task collaboration* means that both T_H and T_R are performed via appropriate human control, and varying level/degree of robot autonomy respectively. Thus, both "human control" and "robot autonomy" are the basic elements that a human and a robot can share and trade with each other respectively to achieve $T_{S\&T}$ (i.e. semi-autonomous control). In both cases, to perform the appropriate actions (i.e. changes in human control and robot autonomy), it invariably involves sharing of information. If the human and the robot have different perceptions regarding the shared information, they must trade information to clarify any doubt before actual actions can be performed. In short, information sharing and trading is to find out what the other party is doing, what the intention of the other party might be and to resolve any conflict if it arises during task execution. Hence, $T_{S\&T}$ is classified into *human control*, *robot autonomy* and *information* sharing and trading respectively to depict what can be shared and traded between a human and a robot during task execution.

The basic elements discussed above are important because they provide the basic constructs towards the characterisation of $T_{S\&T}$ in different HRI roles and relationships established in Section 2.1. The intention is for describing how semi-autonomous control can be achieved based on the concept of $T_{S\&T}$. This is discussed below.

B. Characterisation of $T_{S\&T}$ in Different HRI Roles and Relationships

The main corollary of the concept of HRT discussed in Section 2.2 is it requires the flexibility in HRI roles transition in order to let both human and robot work as a team. Given the HRI roles discussed in Section 2.1, the concern here is: how are these roles related to the process of $T_{S\&T}$ between human and robot. Here, it is posited that different kinds of HRI roles and relationships will inherently induce different phenomenon of $T_{S\&T}$, ranging from pure task decomposition to more complex task or sub task interactions. This is depicted in Fig. 2, in accordance to the basic elements, i.e. human control, robot autonomy and information.

As depicted in Fig. 2, each of the human-robot roles and relationships concentrates on different aspects of $T_{S\&T}$. Therefore, it will be advantageous if they can be integrated under the same framework to provide effective semi-autonomous control. This is achieved through the concept of the different roles and relationships of the human and the robot within an HRS is to provide multiple levels of human control and robot autonomy. In this context, each level of human control and robot autonomy will map in accordance to roles and relationships, such as those classified in Fig. 2. Issues pertaining to this topic are further discussed in Section 3.2.

3.1.5 Task reallocation (T_{RE})

As discussed in Section 2.3.1, T_{RE} is defined as the reallocation of a current desired input task that is allocated to the human and the robot with a completely new task specification. The consideration of T_{RE} as one of the activity within an HRS leads to the differentiation of two types of $T_{S\&T}$. To distinguish, the terms *local* and *global* are introduced. *Local* $T_{S\&T}$ is defined as the ongoing HRI in performing a desired input task with the aim of improving the current HRS task performance. If interaction roles transition occurs within the same task, it is considered as local $T_{S\&T}$. On the other hand, *global* $T_{S\&T}$ is defined as the reallocation of the desired input task that may involve HRI roles and relationships changes; where the change of role has completely different types of task specifications (e.g. change of role from supervisor-subordinate to master-slave, Fig. 2). This implies that a representation of semi-autonomy must take into the consideration of both local and global $T_{S\&T}$. so as to facilitate seamless human control changes and robot autonomy adjustment.

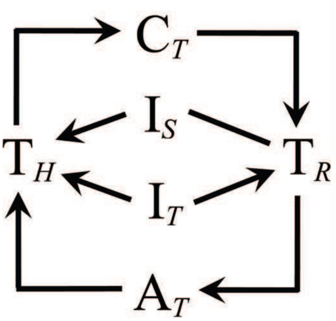
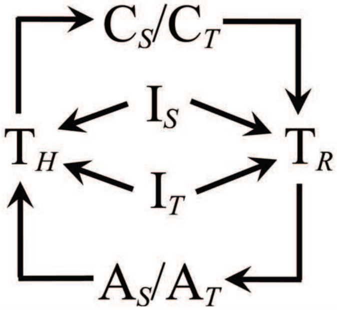
$T_H \leftrightarrow T_{S\&T} \leftrightarrow T_R$	Task sharing and trading ($T_{S\&T}$) between human and robot, extracted from Fig. 1. It is further break down into the basic elements (i.e. human control, robot autonomy and information) to describe the five roles and relationships below.
Master-Slave $T_H \leftarrow I_S \leftarrow T_R$	Trading is not involved. Sharing is in the form of information sharing (I_S) to extend human's sensing to a remote location. For example (Roman, 1993), a submersible robot operated via teleoperation extends the human's sensing (e.g. through video images relay from the robot on-board cameras) to a remote location so that he/she can work safely in the hazardous environment.
Supervisor-Subordinate 	Control trading (C_T) from human to robot is to let human delegate control to robot. On the other hand, the robot needs to adjust its autonomy (i.e. autonomy trading from the robot to the human, A_T) to respond to the human control. Information sharing (I_S) from the robot to the human is for the human to monitor the robot task execution. However, if problem arises, both the human and the robot need to trade information (I_T) to clarify any doubts. An example to illustrate this is the Mars Rover developed to perform planet exploration, scientific measurement and data collection (Pedersen et al., 2003). The subordinate robot can achieve safe and effective navigation to the designated location and perform the desired tasks by augmenting its actions based on its local intelligence and the commands from the human supervisor. In this context, once the control is delegated to the robot (C_T) by the human, the robot will response to the delegation by adjusting its autonomy (A_T) to perform the task. Human typically assumes a monitoring role based on the information feedback by the robot (i.e. I_S). However, if the human has doubt regarding the task or robot status, he/she may exchange information (i.e. I_T) with the robot via dialog.

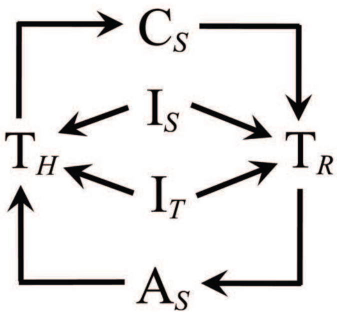
Figure 2. Phenomenon of sharing and trading induce by different human-robot roles and relationships described in Section 2.1

Teacher-Learner



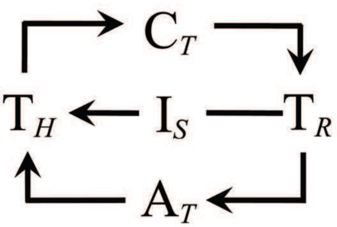
Human teacher and robot learner shared and traded to transfer task knowledge (Klingspor et al. 1997) in the form of information sharing (I_S) and also information trading (I_T) to certain extent to seek understanding and clarification through inquiry by the learner (e.g. in a dialog manner).
Depending on the teaching method, human may either teaches the robot via shared control (C_S) (Suomela & Halme, 2002) or traded control (C_T) (Papanikolopoulos & Khosla, 1992). In this context, the robot needs to share its autonomy (A_S) or traded its autonomy (A_T) to respond to the human control while learning the task. Shared control is normally used if the robot is required to perform the task along with the human and to provide appropriate assistance to the human.

Partner-Partner



Human control sharing (C_S), from human to robot, and robot autonomy sharing (A_S), from robot to human, are to let the robot provides "active" assistance to the human by supporting perception and cooperative task execution. Information sharing (I_S) between robot and human is for the human to monitor the robot task execution, and also for the robot to monitor the human control actions and intention so as to know when to provide appropriate assistance to the human. Similar to that of supervisor-subordinate, if problem arises, both human and robot need to trade information (I_T) to resolve conflicts and coordinate activities.
An example to illustrate this comes from the rehabilitation application (e.g. Martens et al., 2001; Wasson & Gunderson 2001; Bourhis & Agostini, 1998). To provide assistance to the handicapped human user, the robot is normally equipped with high-level of artificial sensing and intelligent for navigation and reasoning. In this application, shared control is widely used to envisage a tight cooperation between the human and robot. Generally, both human and robot might cooperate as follows: the human brings his/her perception and interpretation of the close environment abilities to control the robot via control sharing (C_S). The robot, on the other hand, brings its highly autonomous mobility ability and its knowledge concerning a global model of the environment, moves in to response to the human control by adapting its autonomy (i.e. A_S) to prevent collision with any obstacles.

Fully Autonomous



Sharing is in the form of information sharing (I_S) for human to monitor the robot task execution. Trading is in the form of human control trading (C_T) and robot autonomy trading (A_T) for starting and stopping the robot operation. Starting is normally performed by the human, but stopping can either be initiated by the human or the robot.
A typical example is an intelligent vacuum cleaner (Fiorini & Prassler, 2000) that can operate without any human guidance and control once its start to operate.

Figure 2. Continue.

3.2 Discussion on framework formulation

The definition given in Section 3.1 indicates that semi-autonomous control must be represented with respect to a task, and that humans and robots must actively use its capabilities to pursue this underlying task via $T_{S\&T}$. In the context of $T_{S\&T}$, the aim of this section is to discuss how a framework formulated for semi-autonomy can be used to assist in the design and development of a cooperative HRS. To facilitate, a list of basic questions are considered as follows. Each of these questions is further discussed in Section 3.2.1 to 3.2.6 respectively.

- Why should human and robot share and trade?
- When should human and robot share and trade?
- How does human and robot know when to share and trade?
- How does human and robot share and trade?
- What triggers the change from sharing to trading (or vice versa)?
- Who is in charge of the sharing and trading process?

3.2.1 Why should human and robot share and trade?

In the context of performing an HRS task, $T_{S\&T}$ between a human and a robot is essential to let the human and the robot work together in different task situations and to ensure the overall system performance is achieved during task execution. By specifying in this manner, it does not mean the human and the robot share and trade only to deal with errors or contingency situations. They may even share and trade to provide appropriate assistance to each other during "normal operation", e.g., to let human assists a robot in object recognition, decision-making, etc. or to let a robot assists human in remote sensing such as obstacle avoidance and guidance. This implies that they may simply share and trade to strive for better system performance or to ensure that the system performance does not degrade when the other team mate is performing the HRS task. As such $T_{S\&T}$ process between the human and the robot may occur in an arbitrary manner, it is not feasible to pre-programme such $T_{S\&T}$ process. The "conditions" to invoke $T_{S\&T}$ must be based on the human and the robot current awareness and perception of the ongoing task execution. This topic is discussed below.

3.2.2 When should human and robot share and trade?

An intuitive view of looking into this question is based on the invocation of specific task events. It is possible to envisage a range of invocation events in accordance to the application tasks and invoke them based on the available information in the HRS. An advantage of this is that it directly addresses the possible sharing and trading strategies. From the extreme of initial task delegation to task completion, a spectrum of events can occur during task execution. Within this spectrum, three types of events to invoke or initiate a $T_{S\&T}$ process are distinguished. The first is termed *goal deviations* where the $T_{S\&T}$ process would be invoked by human intervention. This highlights how human assists' robot. The notion of *goal* here does not necessarily refer only to the goal of achieving a specific task, but also to the goal of attaining the overall task of the HRS. The word *deviation* refers to the departure from normal interactions between the robot and its task environment resulting in the robot being unable to achieve the goal. This also includes abnormalities arising during task execution. This may be due to either unforeseen changes in the working environment that cannot be managed by the robot; where an undesirable functional mapping from perception to action causes the robot to "misbehave" (e.g. due to sensing failures).

The second event is *evolving situation* in which the $T_{S\&T}$ process would be invoked by the robot to veto human commands. This highlights how robot assists' human. The types of robot's veto actions can be loosely classified into *prevention* and *automatic correction*. Prevention implies that the robot will only impede the human actions but make no changes to it. The human is responsible for correcting his own actions. An example is when the robot simply stops its operation in a dangerous situation and provides the necessary feedback to the human to rectify his commands. On the other hand, automatic correction encompasses prevention and rectification of human commands simultaneously. Depending on the task situation, the robot may or may not inform the human how to correct his actions. For example, to prevent the human from driving into the side wall when teleoperating through a narrow corridor, the mobile robot maintains its orientation and constantly corrects the side distance with respect to the wall to align with it. In this case, the human may not be aware of this corrective action and he/she is able to drive the robot seamlessly through the corridor. According to Sheridan's (1997) ten-level formulation of system autonomy, both prevention and automatic correction are positioned at level seven or higher, i.e. the "system performs the task and necessarily informs the human what it did". This is because it is the robot that judges whether the situation is safe or unsafe, as the human is unable to judge.

Finally, the third event is when both the human and the robot *explicitly request assistance* from each other. In such an event, the $T_{S\&T}$ process between the two is mixed initiated, where each one strives to facilitate the individual activities in accordance to the task situation.

3.2.3 How does human and robot know when to share and trade?

Given the characterisation of $T_{S\&T}$ in different HRI roles and relationships in Fig. 2, a basic concern towards the achievement of seamless HRI is the need for each team-mate to be able to determine and be aware of and recognise the current capabilities/limitations of each other's during the process of $T_{S\&T}$. The ability for the human and the robot to recognise and identify when to share and trade control/autonomy/information so as to provide appropriate assistance to each other is essential in developing an effective HRT. To enable the robot to assist human, the robot needs to develop a model of the interaction process based upon readily available interaction cues from the human. This is to prevent any confusion during control mode transition. Just as robots need to build a model of the interaction process (and the operating environment) to ensure effective $T_{S\&T}$, it is also important for human to develop a mental model regarding the overall operation of an HRS (e.g. the operation procedures/process, robot capabilities, limitations, etc.), to operate the system smoothly.

A good guide in ensuring that the human is in effective command within a scope of responsibility is the principles from Billings (1997, pp. 39-48). For the human to be involved in the interaction process, he/she must be informed of the ongoing events (to provide as much information as the human needs from the robot to operate the system optimally). He/she must be able to monitor the robot or alternatively, other automated processes (i.e. information concerning the status and activities of the whole system) and be able to track/know the intent of the robot in the system. A good way to let human know the intention of the robot is to ensure that, the feedback from the robot to the human indicates the "reason" for the invocation or initiation action during HRI. This implies that if the robot wants to override the human commands, the robot must provide clear indication for the human to know its intention to prevent any ambiguities. For example, during manual teleoperation, when the robot senses that it is in danger (e.g. colliding into an obstacle), the robot may stop the operation and send a feedback to warn the human in the form of a simple dialog.

3.2.4 How does human and robot share and trade?

As discussed in Section 2.3.1, the considerations of how does a human and a robot share and trade in response to changes in task situation or human/robot performance is based on the paradigm of RAH-HAR. Given the different types of cooperation strategies invoked by this paradigm (Table 1), the challenge is how $T_{S\&T}$ based on RAH-HAR capabilities can be envisaged. To address, consider the characterisation of $T_{S\&T}$ in different human-robot roles and relationships in Fig. 2. Based on this characterisation, Fig. 3 is presented to depict how these human-robot roles and relationships can be employed in designing a range of task interaction modes from "no assistance provided to the human by the robot" to "no assistance provided to the robot by the human" for the human and the robot to share and trade control. Consequently, this depicts how semi-autonomous control modes can be designed.

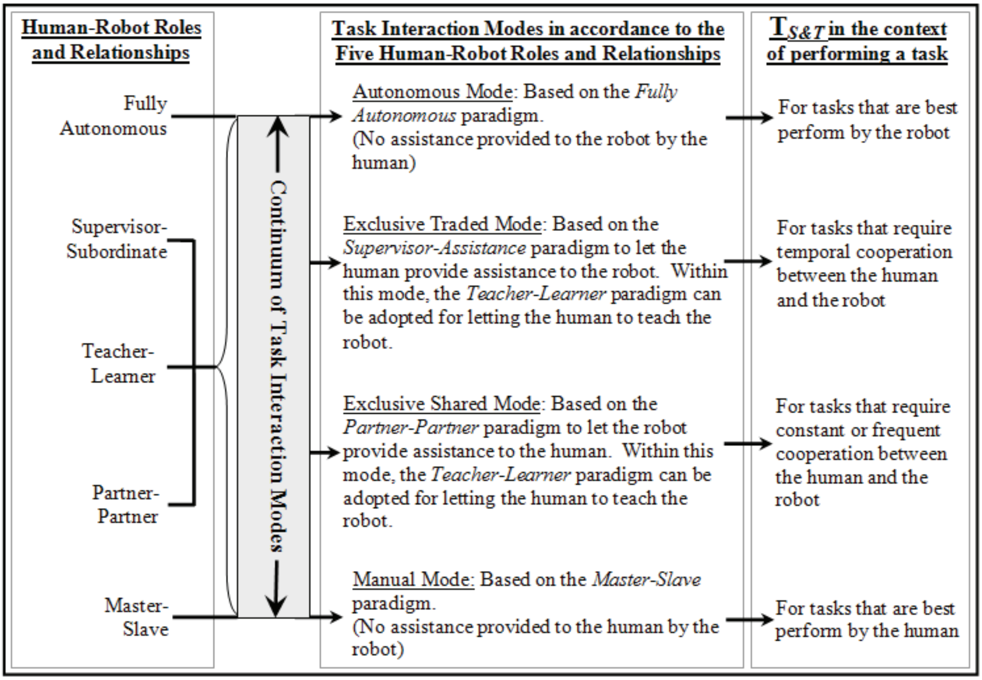


Figure 3. Range of task interaction modes in accordance to the characterisation of $T_{S\&T}$ in different human-robot roles and relationships depicted in Fig. 2