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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.

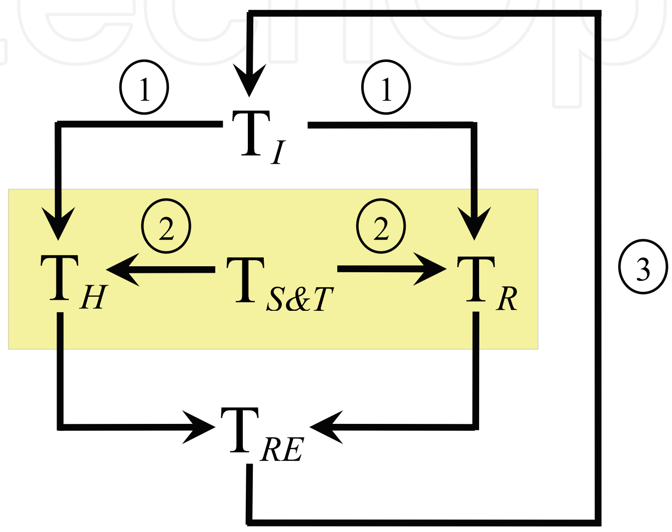


Figure 1: Activities within a Human-Robot System

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.

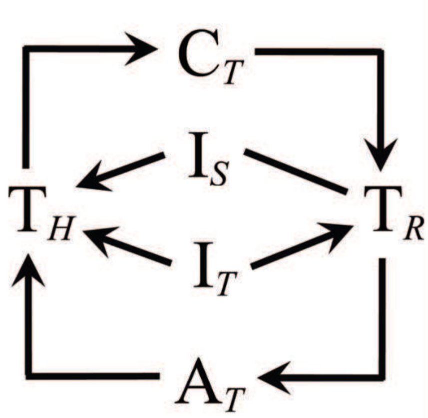
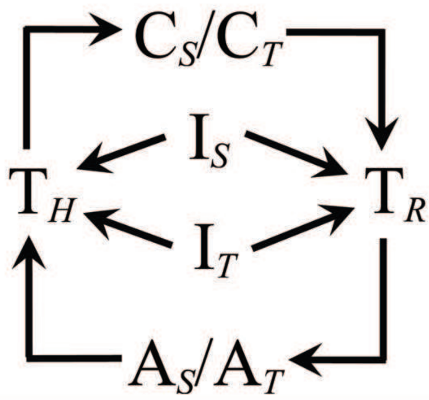
$T_H \leftrightarrow T_{S\&T} \leftrightarrow T_R$	Task sharing and trading ($T_{S\&T}$) between human and robot, extracted from Fig. 1. It is further break down into the basic elements (i.e. human control, robot autonomy and information) to describe the five roles and relationships below.
Master-Slave $T_H \leftarrow I_S \leftarrow T_R$	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.

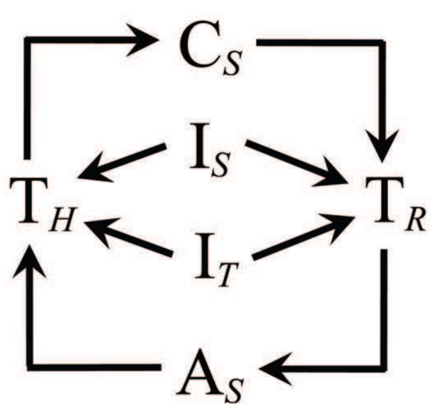
Figure 2. Phenomenon of sharing and trading induce by different human-robot roles and relationships described in Section 2.1

Teacher-Learner



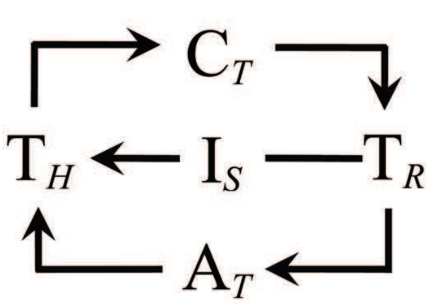
Human teacher and robot learner shared and traded to transfer task knowledge (Klingspor et al. 1997) in the form of information sharing (I_S) and also information trading (I_T) to certain extent to seek understanding and clarification through inquiry by the learner (e.g. in a dialog manner).
Depending 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.

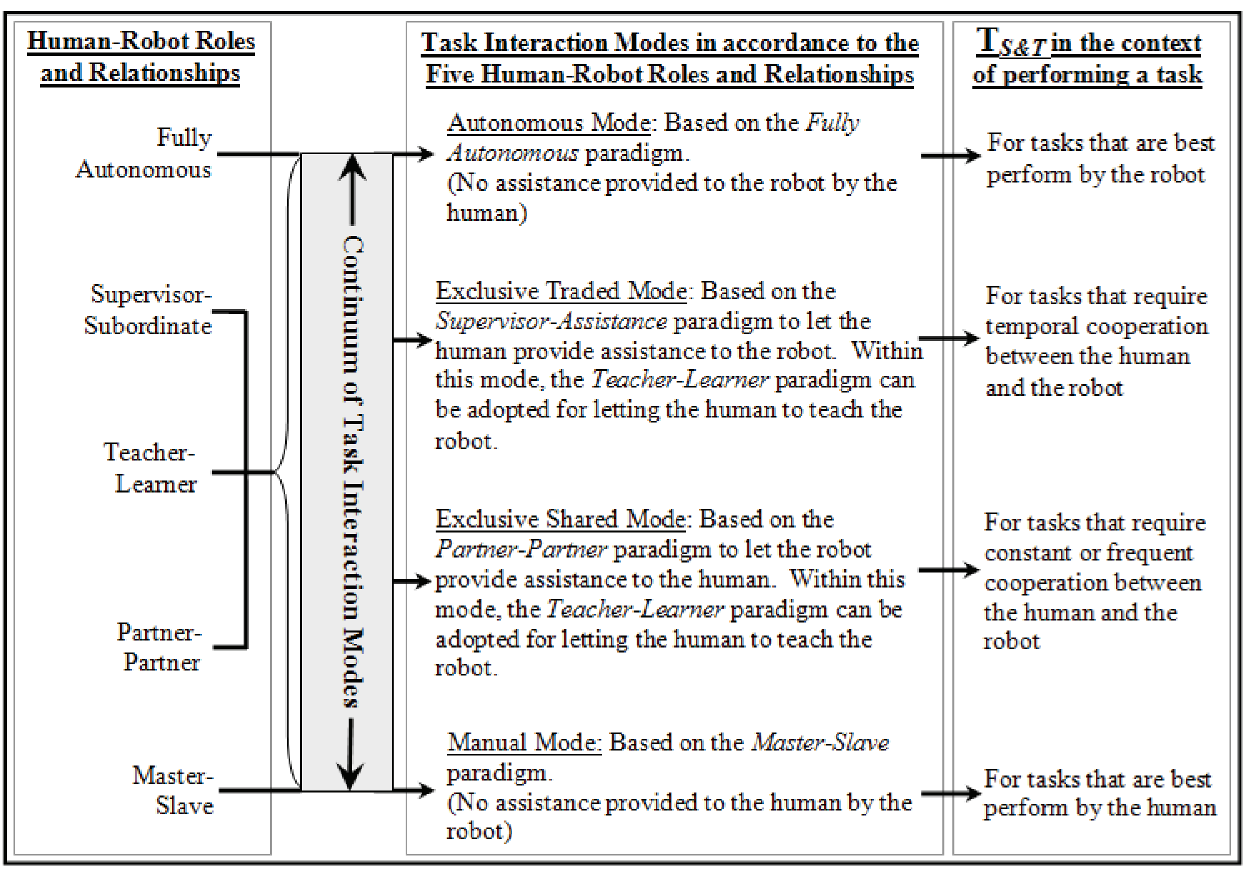


Figure 3. Range of task interaction modes in accordance to the characterisation of $T_{S\&T}$ in different human-robot roles and relationships depicted in Fig. 2

As shown in Fig. 3, to characterise the five human-robot roles and relationships, four discrete levels of interaction modes namely, *manual mode*, *exclusive shared mode*, *exclusive traded mode* and *autonomous mode* are defined. By defining sharing and trading in this manner does not mean that trading does not occur in sharing, or vice versa. Here, the term "exclusive" is used to highlight that the shared mode is exclusively envisaged to let the *robot assists human*, while the traded mode is exclusively envisaged to let the *human assists robot*. The reason of placing the shared mode below the traded mode is based on the degree of human control involvement. This implies that in exclusive shared mode, human is required to work together with the robot by providing continuous or intermittent control input during task execution. On the other hand, in exclusive traded mode, once the task is delegated to the robot, the human role is more of monitoring rather than of controlling or requires "close" human-robot cooperation, as compared to the exclusive shared mode. Therefore, the interactions between the human and the robot in this mode resemble the supervisor-subordinate paradigm instead of a partner-partner like interaction as in the exclusive shared mode.

A. Level and Degree of Task Interaction Modes

Fig. 3 depicts different *level* of human control and robot autonomy. This is for global $T_{S\&T}$ (Section 3.1.5), where each level represents different type of task specifications. To ensure that human maintains as the final authority over the robot (discussed in Section 3.2.6), level of task interaction mode transitions can only be performed by the human. Within each level, a degree of mixed-initiative invocation strategies (Section 3.2.2 and further discussed in Section 3.2.5) between human and robot can be enviaged to facilitate local $T_{S\&T}$ (Section 3.1.5). An approach to design invocation strategies is to establish a set of policies or rules to act as built–in contingencies with respect to a desired application. Based of these policies, the robot can adjust its degree of autonomy appropriately to response to the degree of human control changes or unforeseen circumstances during operation. To illustrate, Fig. 4 provides a basic idea of how this can be envisaged, by setting up a scale of operation modes, which enables the human to interact with the robot with different degree of human control involvement and degree of robot autonomy. The horizontal axis represents the degree of robot autonomy, while the vertical axis corresponds to the degree of human control involvement.

As shown in Fig. 4, 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. (2002). They are: *possible actions*, *independently achievable actions*, *achievable actions*, *permitted actions* and *obligated actions*. Based on these five actions, constraints can be imposed so as to govern the degree of robot autonomy (e.g. defined using a set of perception-action units) within each level of task interaction modes (Fig. 3). In this manner, human can establish preferences for the autonomy strategy the robot should take by changing or creating new rules. Consequently, rules can be designed to establish conditions where a robot must ask for permission to perform an action or seek advice from the human about a decision that must be made during task execution in accordance to the capabilities of the robot.

Given the range of task interaction modes defined in Fig. 3 and Fig. 4, to facilitate semi-autonomous control, concern pertaining to what triggers the change from sharing to trading (or trading to sharing) must be addressed. This is discussed in the following section.

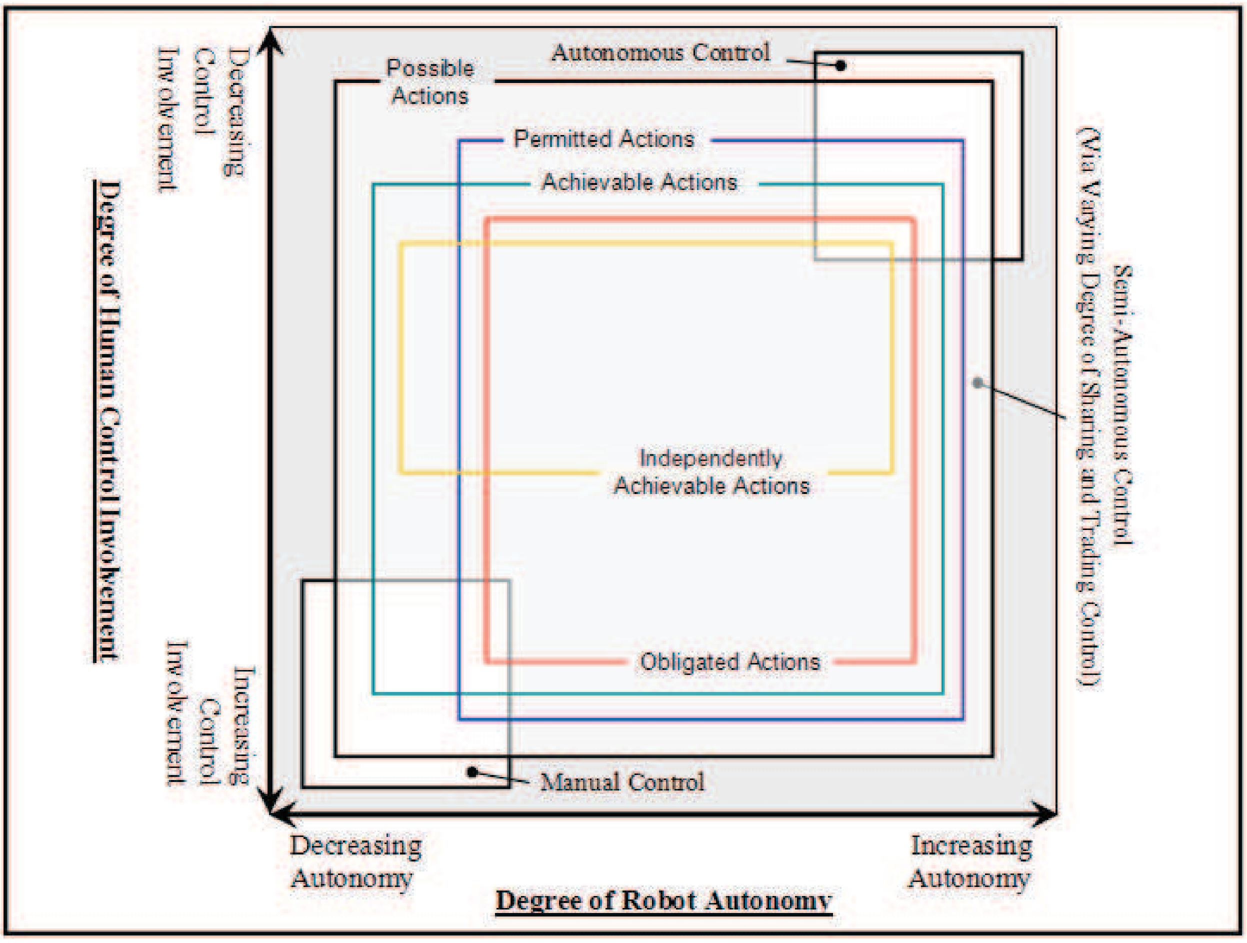


Figure 4: Control modes based on robot autonomy and human control involvement in accordance with varying nested ranges of action of robot

3.2.5 What triggers the change from sharing to trading (or trading to sharing)?

In accordance to the range of task interaction modes defined in Fig. 3, a transition from sharing to trading (or vice versa) may involve in a total new task specifications (i.e. global $T_{S\&T}$) or within the context of a same task specifications (i.e. local $T_{S\&T}$). Both global and local $T_{S\&T}$ are defined in Section 3.1.5 respectively. To discuss what triggers the change from sharing to trading (or vice versa) in both types of $T_{S\&T}$ process, two types of trigger, namely *mandatory* and *provisional* for global $T_{S\&T}$ and local $T_{S\&T}$ respectively are distinguished.

- *Mandatory Triggers* are invoked when there is a change of task plan by the human due to environmental constraints that may require different control strategy (e.g. from shared control to traded control), when the robot has completed performing a task leading to the specification of a new task that may required different control strategy or when task performance of the robot is perceived to be unsatisfactory resulting in human to use other control strategy, to name a few.
- *Provisional Triggers* are invoked when the human or the robot wants to assist each other to strive for better task performance. In this context, a change from sharing to trading can be viewed from a change from the robot assisting human to human assisting the robot, or vice versa in the case of from trading to sharing.

3.2.6 Who is in charge of the sharing and trading process?

The paradigm of RAH-HAR requires that either the human or the robot be exclusively in charge of the operations during $T_{S\&T}$. This means that the robot may be in authority to lead certain aspect of the tasks. This may conflict with the principle of human-centred automation, which emphasises that the human must be maintained as the final authority over the robot. As this issue of authority is situation dependent, one way to overcome this is to place the responsibility of that $T_{S\&T}$ process to the human. This means that the human retains as the overall responsibilities of the outcome of the tasks undertaken by the robot and retains the final authority corresponding with that responsibility. To facilitate, apart from giving the flexibility to delegate tasks to the robot, the human need to receive feedback (i.e. what the human should be told by the robot) on the robot intention and performance (e.g. in term of the time to achieve the goal, number of mistakes its make, etc.) before the authority is handed over to the robot. To delegate tasks flexibly, the human must be able to vary the level of interaction with specific tasks to ensure that the overall HRS performance does not degrade. Ideally, the task delegation and the feedback provided should be at various levels of detail, and with various constraints, stipulations, contingencies, and alternatives.

4. Application of semi-autonomous control in telerobotics

In Section 3, a framework for semi-autonomous control had been established to provide a basis for the design and development of a cooperative HRS. The type of HRS addressed here is a telerobotics system, where the robot is not directly teleoperated throughout the complete work cycles, but can operate in continuous manual, semi-autonomous or autonomous modes depending on the situation context (Ong et al., 2008). The aim of this section is to show how this framework can be applied in the modelling and implementation of such system.

4.1 Modelling of a telerobotics system

In the formulated semi-autonomous control framework, the first phase towards the development of a telerobotics framework is the *application requirements and analysis phase*. The emphasis of this phase is to identify and characterise the desired application tasks for task allocation between humans and robots. Given the desired inputs tasks for allocation, the second phase towards the telerobotics framework development is the *human and robot integration phase*. The primary approach of integrating human and robot is via the concept of $T_{S\&T}$, in accordance to how human and robot assist each other. This section discusses these two phases; presented in Section 4.1.1 and 4.1.2 respectively. The final phase which is the implementation of the telerobotics system is discussed in Section 4.2. Subsequently, proof-of-concept experiments are presented in Section 4.3 to illustrate the concept of semi-autonomous control.

To provide an overview of how the first phase and second phase described above are involved in the development of the sharing and trading telerobotics framework, a conceptual structure of an HRS is depicted in Fig. 5.

4.1.1 Application requirements and analysis phase

The first component in Fig. 5 is the task definition of a particular application goals and requirements which involves the translation of a target application goals and requirements into a "task model" that defines how a telerobotics system will meet those goals and requirements. This includes conducting studies to assess the general constraints of the potential technology available (e.g. different types of sensing devices) and environment constraints (e.g. accessibility, type of terrain) that may be useful for the telerobotics system under design. For this research, the type of applications considered are those based on mobile telerobotics concept, such as planetary exploration, search and rescue, military operation, automated security, to name a few. This implies that the characteristic of the desired input task (i.e. T_I, Fig. 1) of such applications is to command a mobile robot (by a human) to move from one location to another location while performing tasks such as surveillance, reconnaissance, objects transportation, etc.

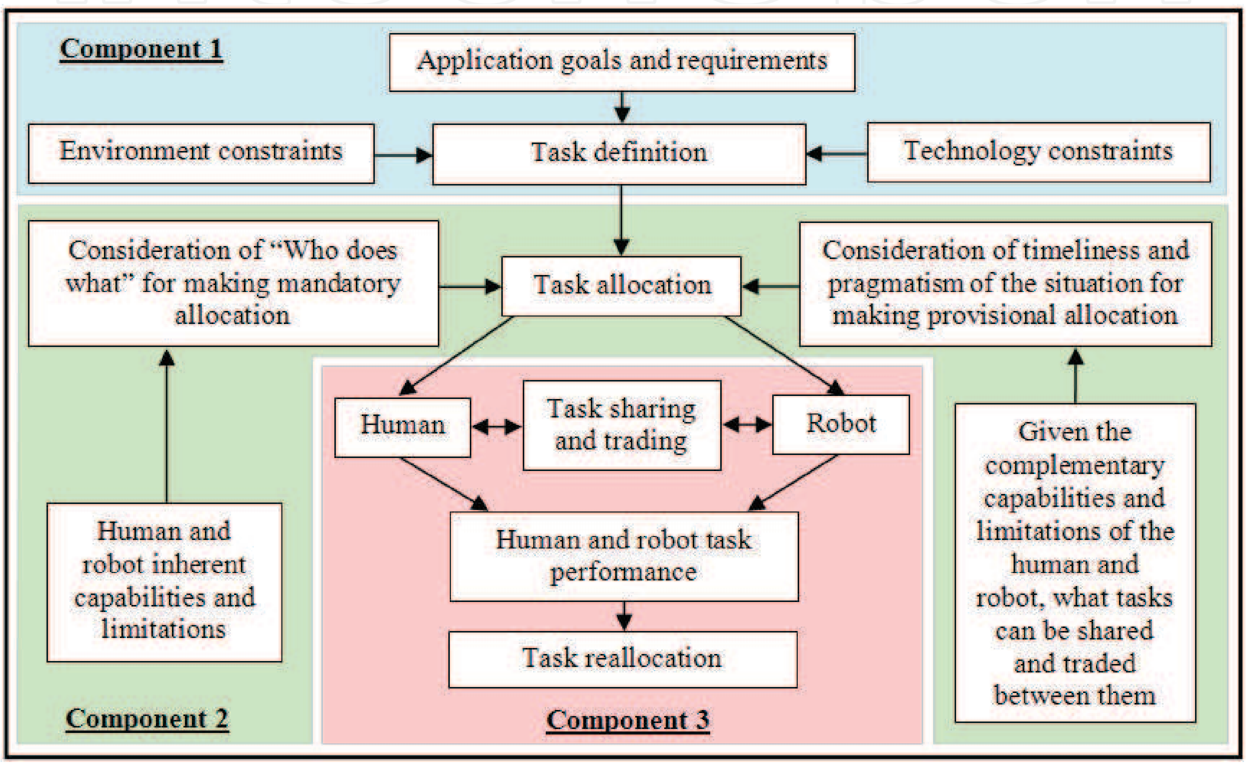


Figure 5. A conceptual structure of an HRS

4.1.2 Human and robot integration phase

The second component in Fig. 5 is the allocation of the desired input tasks to human (i.e. T_H, Fig. 1) and robot (i.e. T_R, Fig. 1). Possible analyses to the type of tasks that can only be allocated to human and robot (i.e. "who does what") are discussed in Section 3.1.2 and 3.1.3 respectively. The difficult part is to consider tasks that can be performed by both human and robot. For example, the T_I discussed in Section 4.1.1 (i.e. *moves from one location to another location*) implies three fundamental functions: *path planning*, *navigation* and *localisation*. Both human through control of robot by teleoperation and robot have the capabilities to perform these functions. The main consideration is who should perform these functions or is it possible for human and robot to cooperate to perform these functions. In accordance to the paradigm of RAH-HAR (Section 3.1.4), this is not a problem because this paradigm takes into the consideration of timeliness and pragmatic allocation decisions for resolving conflicts/problems arising between human and robot. Therefore, it allows human and robot to perform the same function. The advantage of allowing human and robot perform the same function is that they can assist each other by taking over each other task completely when the other team member has problem performing the task. To achieve such a complementary and redundancy strategy, the approach by RAH-HAR is to develop a range of task interaction modes for human and robot to assist each other in different situations as described in Section 3.2.4. The four main task interaction modes are *manual mode*, *exclusive shared mode*, *exclusive traded mode* and *autonomous mode* as shown in Fig. 3. The two extreme modes (i.e., manual and autonomous) are independent to each other. They are also independent to the exclusive shared and traded modes. On the other hand, the dependency of the exclusive shared and traded modes depends on how human use the interaction modes to perform the application task. For example, to command a robot to a desired location based on environment "landmarks", the robot must first learn to recognise the landmarks so as to perform this navigation task. In this situation, the exclusive traded mode is dependent on the exclusive shared mode. This is because this mode facilitates robot learning of the environmental features to the desired location via teleoperation by the human.

A. Robot Capabilities

It is reasonable to argue that a human is currently the most valuable agent for linking information and action. Therefore, in an HRS, the intelligence, knowledge, skill and imagination of the human must be fully utilised. On the other hand, robot itself is a "passive component", its' level/degree of autonomy depends on the respective robot designer or developer. As highlighted in Section 2.2, for a human-robot team, the considerations are no longer just on robotic development but rather more complex interactive development in which both the human and the robot exist as a cohesive team. Therefore, for the robot to assume appropriate roles to work with the human counterpart, the robot must have the necessary capabilities. In accordance with the research in robotics (Arkin, 1998) and AI (Russell & Norvig, 2002), the capabilities required by a robot are numerous but may classify along four dimensions. They are *reasoning*, *perception, action* and *behaviours* (i.e. basic surviving abilities and task-oriented functions) as depicted in Fig. 6.

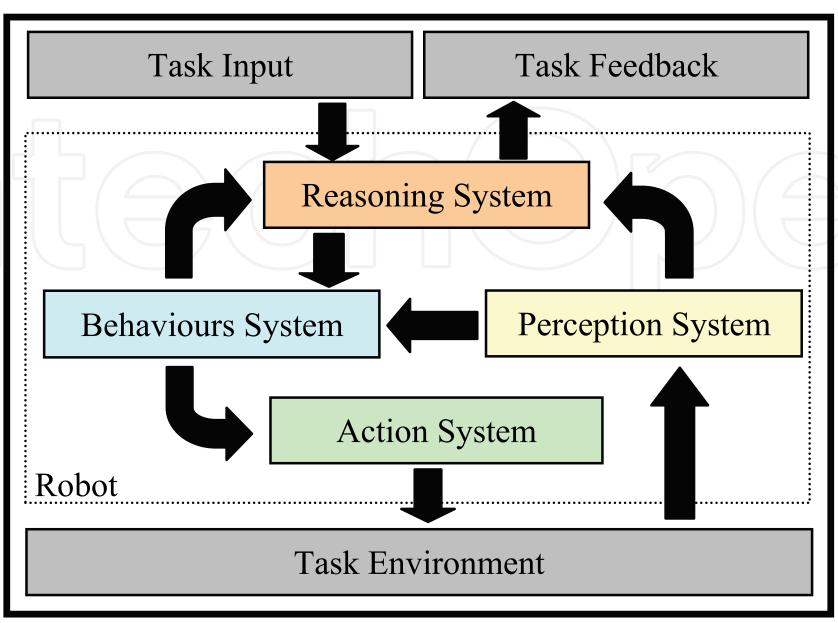


Figure 6. The Relationship between different capabilities of a robot

Reasoning: A robot must have the ability to reason so as to perform tasks delegated by human. In AI, the term "reasoning" is generally used to cover any process by which conclusions are reached (Russell & Norvig, 2002, pp. 163). By specifying in this manner, reasoning can be used for a variety of purposes, e.g. to plan, to learn, to make decision, etc. In robotics, *planning* and *learning* have been identified as the two most fundamental intelligent capabilities a robot must be imbued with so as to build a "fully autonomous robot" that can act without external human intervention (Arkin 1998). However, due to the fact that a robot must work in a real-world environment that is continuous, dynamic, unpredictable (at least from the robot's point of view), and so forth, the goal of building such a fully autonomous robot has not yet been achieved. In the context of planning and learning in an HRS, human may assist the robot in performing these functions. For example, the human can assist in solving "nontrivial" problems by decomposing the problem that must be solved into smaller pieces and let the robot solve those pieces separately. In the case of learning, human may teach the robot to perform a particular task via demonstration (Nicolescu & Matarić, 2001). However, apart from learning from the human, the robot must also learn from its task environment (e.g. through assimilation of experience) so as to sustain itself over extended periods of time in a continuous, dynamic and unpredictable environment when performing a task. A good discussion of different robot learning approaches and considerations can be found in (Sim et al. 2003). However, to plan or learn, the robot must have a perception system to capture incoming data and an action system to act in its task environment. This is discussed below.

Perception: A perception system of a robot is in the front line against the dynamic external world, having the function as the only input channel delivering new data captured from outside world (i.e. task environment) to an internal system (e.g. the software agents) of the robot. The perceptual system can play a role of monitoring actions by identifying the divergence between observed state and expected state. This action monitoring to ensure correct response against a current situation by examining an action in-situ should be an indispensable capability particularly in dynamic uncertain environments, in which the external world may change. Therefore, competent perceptual system would significantly contribute to improve the autonomy of a robot. Specifically, this is essential for the robot to monitor human control behaviours so as to provide appropriate assistance to the human. Through this, task performance can be improved (Ong et al. 2008).

Action: An action system of a robot is the only output channel to influence the external world with the results of deliberation (i.e. reasoning) from the internal system. Taking appropriate action in a given moment is one of the fundamental capabilities for an intelligent robot. How long a robot deliberates to find a sequence of actions to attain a goal is a critical issue particularly in real-time task domain. Sometimes it is rational to take actions reactively without planning if the impacts of those actions are minor to the whole accomplishment for the goal and easy to invoke, in emergent situations that require immediate actions.

Behaviours: Finally, a robot must have a set of behaviours to perform particular application tasks. This can range from basic behaviours such as point-to-point movement, collision prevention, obstacle avoidance to more complex task behaviours such as motion detection, object recognition, object manipulation, localisation (i.e. determining robot own location), map building, to name a few.

4.2 Implementation

Based on the system framework established in Section 4.1, this section outlines the design approach and described the system architecture of the telerobotics system. Implementations have been made on the Real World Interface (RWI) model ATRV-Mini™ and the ATRV-Jr™, the Segway-RMP™ (200) and the gasoline engine ARGO™-Vanguard 2, as depicted in Fig. 7.

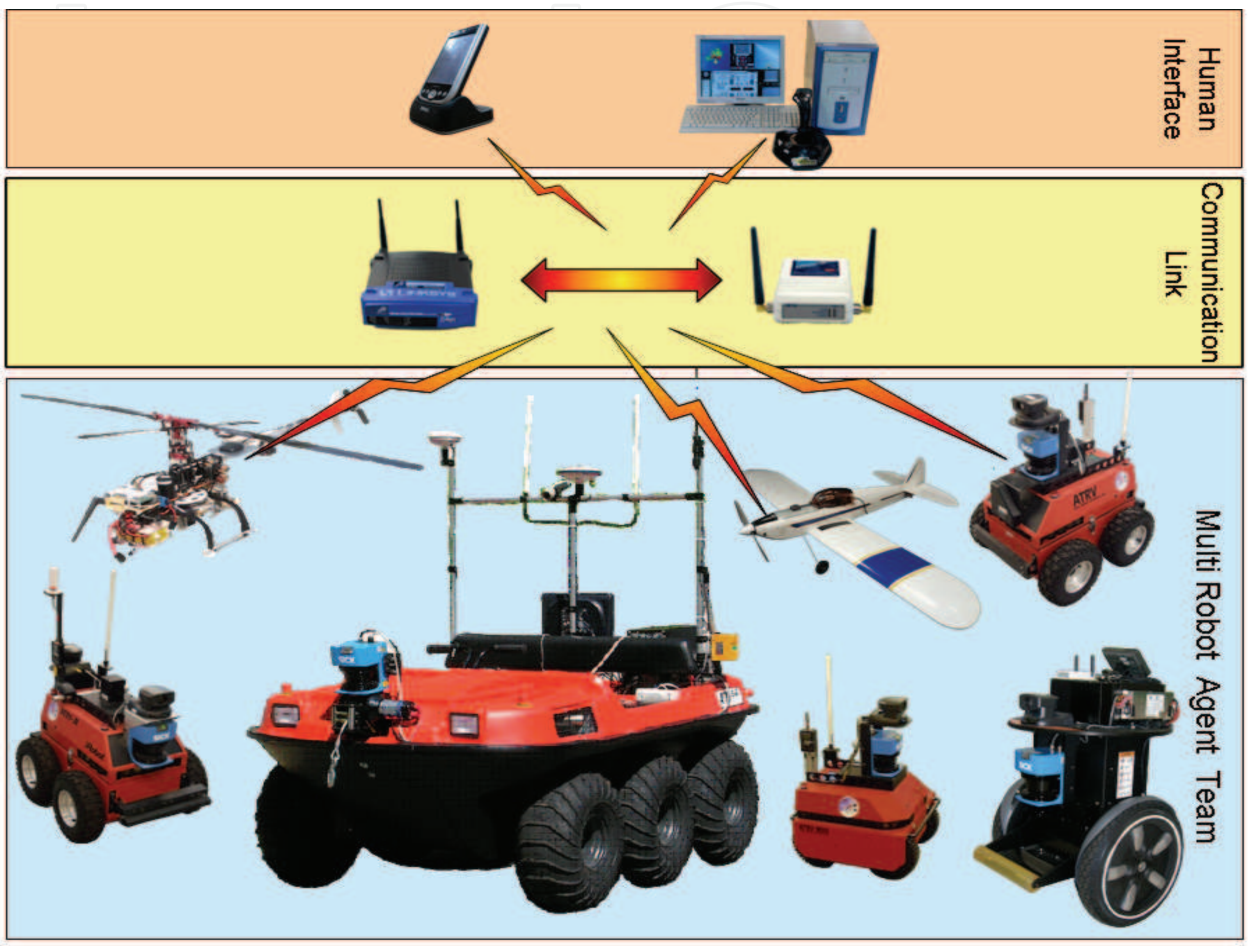


Figure 7. An overview of the telerobotics system setup

The technological considerations are that a telerobotics vehicle requires the following basic components to facilitate human control. Firstly, it must have adequate sensors to perform the desired tasks, e.g. navigation. For example, range sensors for obstacles avoidance, detection and location sensors to determine its location. Secondly, it must have some means of communication transceivers to communicate with the human control interface. Finally, the robot must have embedded computation and program storage for local control systems. That is, a “computer ready” mechatronic system for automated control of the drive, engine and brake system. This is to facilitate the interpretation of command from the human control interface and translate it into signals for actuation. Fig. 8 provides an overview of one of our implemented robotic vehicle, a COTS off-road all-terrain utility vehicle, the ARGO™ that is equipped with the components described above. The main characteristic of this vehicle is its ability to travel on both land and water. This amphibious vehicle is powered by a 4-cycle overhead valve V-Twin gasoline engine with electronic ignition. It can travel at a cruising speed of 35 km/h on land, and 3 km/h on water.

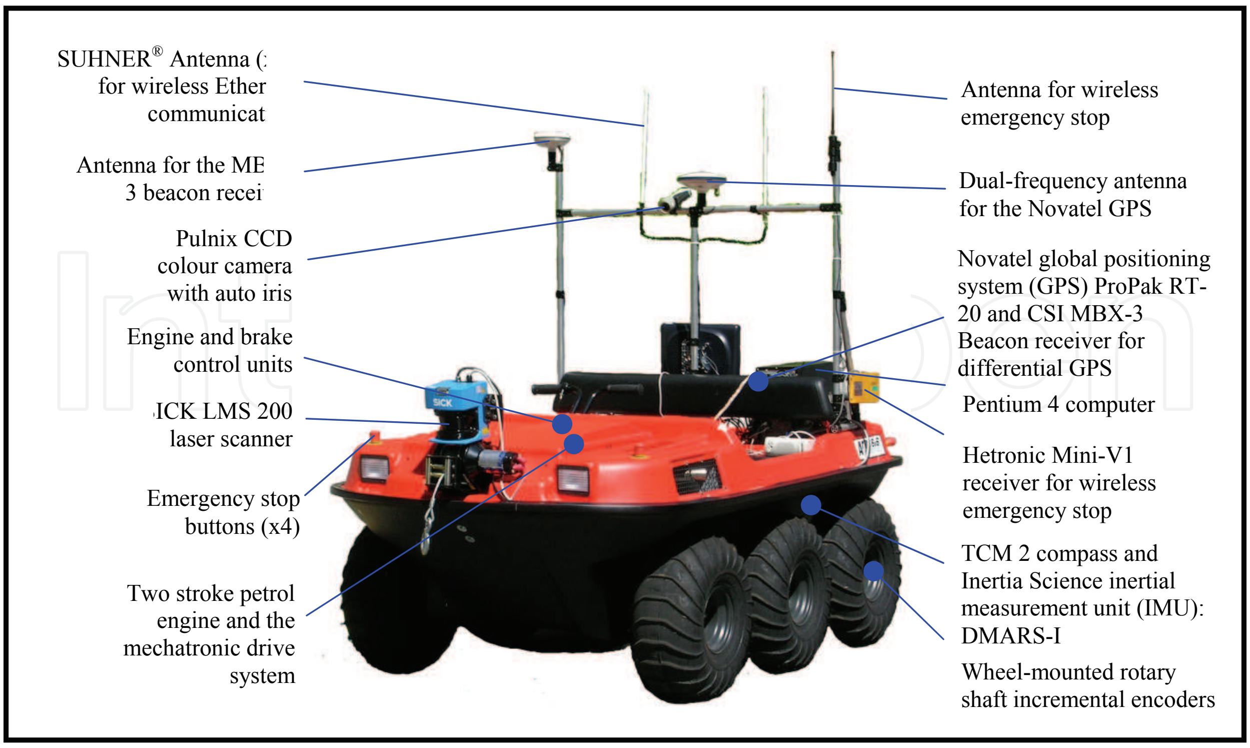


Figure 8.The customised ARGO™ - Vanguard 2 (6x6) amphibious robot

4.2.1 Telerobotics system architecture

The principal part of a robot is the control architecture; it is in charge of all the possible movements, coordination and actions of the robot in order to achieve its goal. To facilitate, different control strategies for robotic control have been proposed over the years. These strategies can be characterised from deliberative control, which is highly influenced by the AI research in the 1970s to reactive control, revolutionised by Brooks (1989) in the 1980s. Deliberative control is purely symbolic and representation-dependent but with high-level of intelligence that often requires strong assumption about the world model the robot is in. This control approach is suitable for structured and highly predictable environment. However, in complex, non-structured and changing environments, serious problems (such as computation, real-time processing, symbol grounding, etc.) emerge while trying to maintain an accurate world model. On the other hand, reactive control, which is highly reflexive and representation-free, couples the perception and action tightly, typically in the context of motor behaviours, to produce timely robotic response in dynamic and unstructured worlds (Arkin, 1998). However, this approach has its own difficulty, i.e. the problem of designing a set of perception-action processes or behaviours in order to plan and to specify high-level goals. Consequently, a hybrid control approach based on the advantages of both the traditional deliberative and reactive approaches has since been the de facto standard in robotics research since 1990s (Arkin, 1998). This approach is widely known as three-layer architecture (Gat, 1998), as it requires a sequencing layer (i.e. the middle layer) to coordinate the processes between the deliberative and the reactive layer. Although this system allows the three layers to run independently, it is considered centralised because it requires all the three layers to work together. The telerobotics system architecture depicts in Fig. 9 adopts this approach. The control architecture is hierarchical. It consists of a low-lever controller (i.e. a mechatronic actuation system) to provide functions for automated control of throttle, steering and brakes, and a high-lever controller that determines the desired velocity and steering direction based on a given goal (e.g. go to a location, follow another vehicle, etc.).

The telerobotics system presented in Fig. 8 is complex and composed of a number of subsystems. Each of these subsystems presents its own challenges. In order to provide a roadmap of how the telerobotics system is developed, the subsystems are classified into:

a) *Robot Hardware* – that consists of all the actuators, sensors and communication devices.
b) *Navigation* – that concerns the movement of the mobile robot.
c) *Localisation* – that estimates the position and orientation of the mobile robot.
d) *Planning* – that describes the planning of actions to be performed by the mobile robot.
e) *Interfaces* – that provides the necessary mechanisms for the human to monitor and control the mobile robot.

Schematically, the components of the telerobotics system architecture in terms of these five subsystems are organised into five levels as depicted in Fig. 9. They are classified based on the robot capabilities discussed in Section 4.1.2-A. In accordance to the three layer architecture, the robot hardware and the navigation behavioural system belong to the reactive layer. The localisation and the navigation behavioural/task coordination system belong to the sequencing layer. The planning and the interfaces level belongs to the deliberative layer. Current implementation does not employ a deliberative planner; instead the responsibility of performing its task is given to the human. This implies that the human is not only responsible for specifying the overall system goal but is also responsible for planning, global world modelling, etc. On the other hand, the mobile robot is concerned with lower level goal, for example to find the "best" path via the path planner (e.g. the shortest available path) and responds to external stimuli reactively while moving towards the goals set by the human. Hence, the system architecture can be categorised under hybrid intelligence.

The decomposition of the system architecture into its subsystems encourages modularity in system development. The modular approach allows easy replacement of components in the event of component failures. It also allows experimentation of components with similar functions, an important consideration in the system development.

4.2.2 Design and development of task interaction modes components

As shown in Section 4.1.2, to facilitate semi-autonomous control, multiple/different methods for sensing, navigation, localisation and planning are implemented in a modular manner. This is essential because without these methods, there can be no rendering of assistance between robot and human. Section 4.2.1 only presents the overall implementation and configuration of the telerobotics system; this section presents the achievement of semi-autonomous control via $T_{S\&T}$ between human and robot at system-level.

Given the task interaction modes characterised in Section 3.2.4 (Fig. 3), to understand how these task interaction modes or their sub-modes transit seamlessly at system-level, there is a need to look into the interaction modes components and how they are coordinated. Modes transition which is situation dependent can be initiated by human, by robot or by both the human and the robot (i.e. mixed initiation). The strategies to effect mode transitions (which also provide pre-conditions for modes coordination) are addressed in Section 3.2.2. Two important attributes involved in modes transition is monitoring and intervention. To define the different levels of human and robot intervention, the classic Rasmussen's (1983) Skill-

Rule-Knowledge (SRK) control behaviour model is adopted. The overall concern here is to discuss the components for facilitating modes transition. The components are classified into: *human control*, *robot autonomy*, and *feedback*. The design of these components is discussed below. This includes the discussion of the coordination of these task interaction mode components.

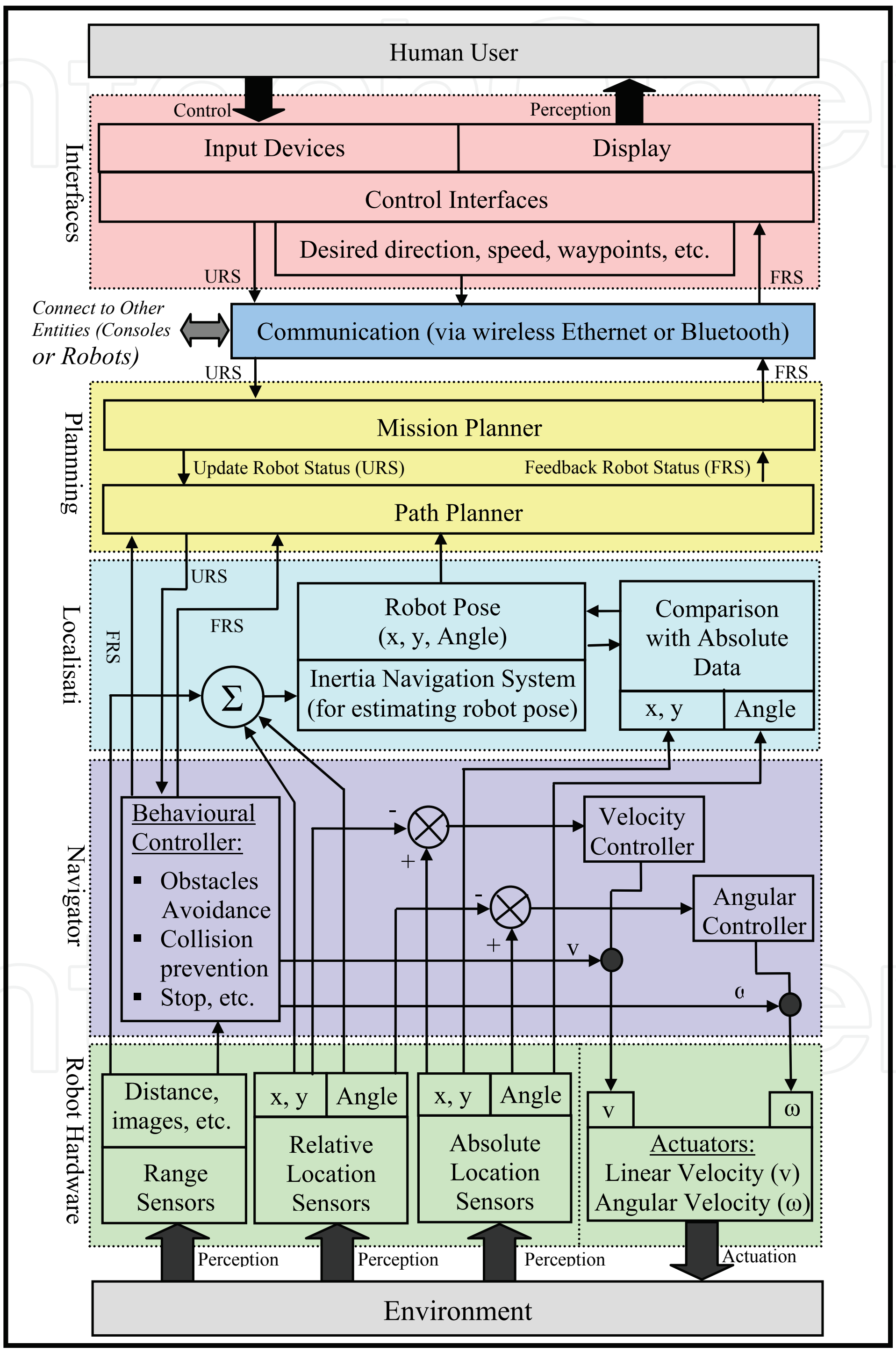


Figure 9. An overview of the telerobotics system architecture

A. Human Control Components

These components are responsible for integrating the human control input into the robotics system. The primary function is to allow human intervention of robotics operations at different levels. In accordance to the Rasmussen's SRK model, the implementation of the human control intervention is classified into three levels as follows:

Level 1. *Skill-based control behaviour*: Piloting or co-piloting of the robot which uses the human perception-motor coordination. This is applied in both the manual mode and exclusive shared mode via continuous human input. The human inputs at this level are rate control of the robot translation and rotation speed.

Level 2. *Rule-based control behaviour*: Command the robot which uses the human perception-decision action to define intermediate navigation goal during task execution. This is applied in exclusive shared mode via human intermittent input. The human input at this level is directional control of the robot heading.

Level 3. *Knowledge-based control behaviour*: Task-level supervision that requires human perception, decision making and planning. This is applied in exclusive traded mode and autonomous mode. The human inputs at this level are as follows: (a) single-point (both relative and absolute) and multi-points (absolute) commands for waypoint navigation; (b) landmarks specification for location-based navigation; and (c) shapes and colours model specification for visual-based task (e.g. object following). Finally, the human inputs can also be in the form of system configurations, such as sensing distance and navigation speed, activation and deactivation of particular sensors, robot autonomy and feedback components specified before operation. This applies at all three levels.

Apart from performing the above functions, the human control components also tries to derive the human control action and intention in real-time. This is to facilitate robot monitoring of the human's behaviours through the exclusive shared mode. The purpose is for the robot to provide appropriate assistance to the human.

B. Components for Enabling Robot Autonomy

Components for enabling robot autonomy control how the robot operates and cooperates with the human. The components are further classified into components for operating autonomy and decisional autonomy. The operating autonomy components provide means for sensing and hardware operation. The decisional autonomy components provide means for the navigation, localisation and planning subsystem described in Section 4.2.1. To understand how the robot varies its degree of autonomy and cooperates with the human within each level of interaction modes, there is a need to discuss the navigation subsystem, where all the behavioural units are situated. The basic behaviours are designed based on the required abilities of a mobile robot to navigate safely in a task environment. The implemented task-level behaviours are customized based on the tasks for an automated security system. Behaviour such as emergency stop uses a fixed autonomy (0 or 1); other behaviours, such as collision prevention, obstacle avoidance, goal seeking, etc. operates with a degree of autonomy varying from 0 to 1. The condition to select which behaviours is based on the task input from a human (or from other robots). The current implemented behavioural units includes behaviour such as emergency stop that uses a fixed autonomy (0 or 1); while other behaviours, such as collision prevention, obstacle avoidance, goal seeking, etc. operates with a degree of autonomy varies from 0 to 1. The conditions to vary the behaviours autonomy are dependent on:

- the strength of the control signal from the human;
- the strength of the corresponding sensors information about the environment, and

- the autonomy of other behaviours.

The condition to select which behaviours should be active is based on the interaction mode the human selected. As this topic is related to the coordination of behaviours, it is further discussed below in Part D.

C. Feedback Components

Feedback is important to ensure that the human is in effective command during task execution (Section 3.2.3 and 3.2.6). The current implementations of the interfaces are being explored on a PC-based station and also on portable devices such as PDA to facilitate different types of HRI (e.g. proximity and remote interactions). Although the interfaces are implemented on different systems, all have similar functions, such as displaying different type of the sensors information from the robot and robot control (i.e. from direct manual to autonomous control). The implementation details of these interfaces are described in Ong et al. (2004).

D. Coordination of Task Interaction Modes

A task interaction modes coordinator is required to coordinate human and robot activities to facilitate $T_{S\&T}$. Consequently, this facilitates the achievement of semi-autonomous control. In accordance to Section 3.2.4-5, a coordinator is required to coordinate system activities both "globally" and "locally". In this implementation, global coordination is achieved directly via interaction mode selection by human. This implies that the human will determine which level of task interaction mode is suitable for performing a particular task either through monitoring or during HRI. Through this, the coordinator will determine the appropriate robot behavioural units to use. This greatly reduces the need of coordinating all the behavioural units locally during task execution and hence requires lower computation. Those behaviours that are not in used are set to a lower priority (or off) according to their process ID. This form of coordination, via priority-based arbitration is used together with superposition-based command fusion to efficiently coordinate the robot behaviours locally. An illustration of this coordination scheme is depicted Fig. 10. The notation representation is as follows: V – Actuator vectors, A – Degree of autonomy, Σ – Summation (superposition-based command fusion) and S – Suppression (priority-based arbitration)

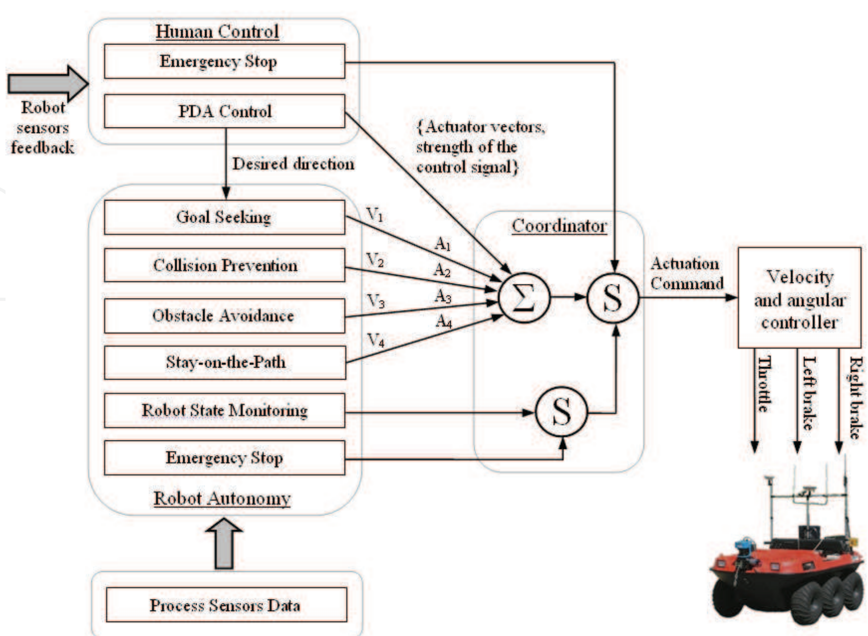


Figure 10. An example of hybrid coordination in exclusive shared mode

4.3 Experimental studies

It is essential that research into robotics be proven by experimental study of concepts and ideas, and validation of algorithms. Many problems in robotics evolve from phenomena that occur during its interaction with a dynamically changing environment which do not lend themselves to a formal treatment. Thus experimental studies of robotics system would preferably be based on real-world experimentation using physical robots, as opposed to the use of simulation (Brooks, 1986). In this context, a widely subscribed approach for the evaluation of robotics system is the use of *proof-of-concept*, which is to show that the system is capable of accomplishing the particular task it is designed for. Consequently, this approach is adopted to investigate the concept of semi-autonomous control invoked by $T_{S\&T}$ (i.e. task sharing and trading) established in Section 3. Different experiments have been conducted to assess the concept of semi-autonomy. This includes:

- The assessment of the cooperation between human and robot from the perspective of how assistance can be provided to the human by the robot. The aim is to establish a basis to show that there is a difference in task performance between robot assistance provided to the human and when no robot assistance is provided. The purpose is to provide a basis for assessing human-robot roles transitions from no assistance to maximum assistance provided to the human by the robot. The results obtained shows that the system performance is improved significantly when the robot provided appropriate assistance to the human as compared to no assistance was provided (Ong et al., 2008).
- The assessment of seamless semi-autonomous control due to local $T_{S\&T}$. As defined in Section 3.1.5, local $T_{S\&T}$ is the ongoing interaction role changes between human and robot in performing a desired input task with the aim of improving the current HRS task performance. The purpose is to show the need of using different human-robot roles and flexibility in roles changing as discussed in Section 2.2. The results obtained shows that a better performance can be achieved if human and robot can change their interaction roles dynamically during task execution as compared to the use of fixed interaction role (Ong et al., 2008).
- The assessment of the cooperation between human and robot from the perspective of how assistance can be provided to the robot by the human. This includes the evaluation of semi-autonomous control due to change of human-robot roles with completely different type of task specification (i.e. global $T_{S\&T}$). The assessment is based on how human assistance can be provided to robot seamlessly in different task situations. One of the main experiments conducted is w*aypoints navigation*: The task is for the human to command the robot(s) from one location to another location via waypoint(s) control as depicted in Fig. 11. Assistance provided to the robot by the human is in the context of planning a safe path for the robot to navigate. This experiment is presented in (Ong et al., 2007).

Finally, to illustrate the functionality and working principles of the concept of semi-autonomy, a simple teleoperation demonstration, using manual and exclusive shared control (Fig. 3) is presented. Here, the task is to allow for the human to teleoperate the ARGO (Fig. 8) from location "A to B". That is, if the ARGO is at location A, the problem is to control the robot's actions so that it moves from A to B. As basic as this task may seem, executing it successfully is critical for many mobile robotics applications.

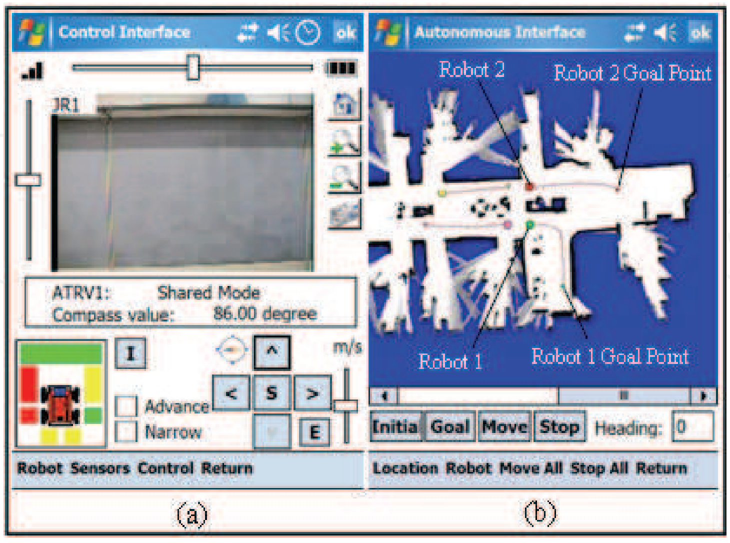


Figure 11. Snapshot of the PDA interface: (a) Control Menu and (b) Waypoint Menu

In the *manual* mode, the human has full control of the robot actions. This includes starting and stopping the engine. The robot takes no initiative except to stop when the wireless communications breakdown. However, the human can configure the robot to take basic initiative to protect itself. Under this safety feature, when the robot approaches an obstacle, the collision prevention behaviour will be activated to decelerate and stop near the obstacle within a safe sensing distance configured by the human. In the context of teleoperation using this mode, the human needs to make adjustments to compensate for drift to ensure the robot motion is straight (e.g. due to travel over uneven terrain). In addition, the human must also make fine adjustments to achieve smooth steering during turning.

In the *shared* mode, both the human and the robot can control same/different aspects of the system concurrently. In contrast to the manual mode, the robot has the capability to automatically accomplish the navigation task by assessing its own status and surroundings, and to decide whether the commands by the human are safe. This includes automatically adjusts for drift, guidance (i.e. stay-on-path) and obstacles avoidance. This relieves the human of detailed control and lets him concentrate on the overall goal of the task. However, as compared to the manual mode, the shared mode could not reach the maximum speed (i.e. 1.8 m/s for this experiment setup) because the robot was constantly reacting to the obstacles in the test environment to ensure safe teleoperation. This is depicted in Fig. 12, which illustrates the semi-autonomous control of the ARGO using a sequence of behaviours (i.e. collision prevention, obstacle avoidance, stay-on-path and goal seeking).

As shown in Fig. 12a-d, when the ARGO approaches an object (i.e. the orange cone), the collision prevention behaviour was first invoked for safe deceleration. Subsequently, the robot assisted the human by performing autonomous obstacle avoidance manoeuvre (Fig. 12e-h) and continues to move forward in accordance to the desired human control direction (Fig. 12i) indicated by the goal seeking behaviour, directed via the path planner. The coordination architecture to achieve this is depicted in Fig. 10.

Figure 12. Montages of the ARGO vehicle during teleoperation under shared mode

5. Discussion and conclusion

In this paper, the development of a framework for semi-autonomous control using the concept of sharing and trading is discussed. This includes the application of this framework in the implementation of a telerobotics system. The purpose of the semi-autonomous control scheme is to facilitate the human and the robot to cope with different aspects of their interactions. By enabling the human to interact with the robot semi-autonomously, the human can decide the most appropriate scheme for performing a task. The main advantage of designing the robot control architecture using the concept of semi-autonomy is the ability for the control system to tolerate shifts in autonomy from manual to full autonomy (Fig. 3). In another words, at each level of interaction mode, the required robot competence is considered from the start of the design stage. The main theme of the semi-autonomous scheme is to design the robotics system as a cooperative endeavour, where both the human and the robot can assist each other.

In general, the implemented control modes based on the concept of semi-autonomy have two important features: *complement* and *redundancy*. The control modes are *complementary* in order to allow for the human and the robot to deal with different aspects of a task. In addition, the control modes are also *redundant* to provide more options for the human to develop strategies to perform the task. This implies that if any control mode fails, the human can use another mode to perform the desired task. In accordance Section 4.3.1, to navigate from location A to B, the human can have the option to either teleoperate the robot to location B using the manual mode or the shared mode. In the context of system implementation, to give the human the abovementioned control flexibility, the robot must imbue with the capabilities to adjust its level of autonomy during operation. To realise, the solution offers in this paper is the integration of the human control and the robot autonomy via an implementation of modular semi-autonomous software architecture for them to interact dynamically.

Although this paper established a comprehensive study on the formulation of a framework for semi-autonomous control, there are other related issues that are not addressed. Firstly, to address the human-robot authority issues it requires that neither human nor robot to be exclusively in charge of HRS task, but rather it requires human to retain as the overall responsibilities of the outcome of the tasks undertaken by the robot and retains the final authority corresponding with that responsibility. This is achieved by giving human both the flexibility in delegating control to the robot at different levels and varying his/her control involvement with the robot at varying degree of task details. However, to develop a truly cooperative HRS, it may not be the best approach, particularly in situation when human does not have the capability to delegate control to the robot or vary his/her control involvement with the robot due to insufficient/poor task feedback. If this happen, the system may be disabled and, thus affect the achievement of seamless HRI. A possible solution is to allow both human and robot to have "equal" authority to correspond to the overall responsibilities of the outcome of tasks together. This implies not just giving the robot the authority to leads certain aspect of a task, but also responsible for the task success or failure of the task. If this can be modelled, a more "synergistic" approach can be provided for addressing the human-robot authority issues. Thus, an extension of this research is to investigate this issue and how it can be incorporated into the current framework.

Second, to envision a "tighter" cooperation between human and robot just as in human-human teamwork requires not only understanding (or modelling) of each other actions and intentions, but may also depend on human's "trust" in interacting with robot. As operations in an HRS can be complex, humans may fail to understand the mechanism of the operations. For instance, robot may operate abnormally under certain conditions. Therefore, the level of trust human has in an HRS is important. If the human trusts the system too much, he/she may become complacent about the behaviour of the robot and may not be vigilant about understanding its effects (this may lead to serious accidents). On the other hand, if the human distrusts the system, the system can be disabled. According to Barber (1983), differing degree of trust impacts all interactions involving people and technology. Trust has been studied in a number of domains. For example in automation, Abe et al. (1999) showed that human's trust in automation is one of the major factors in the usage of automation. Following this, to make seamless semi-autonomous control effective,, the issue of human trusting the robot is important. Logically, trust is not acquired instantaneously; it must be built up gradually. For example, it is based on the experience of controlling the robot to know how it acts. If the action of the robot is predictable, the level of trust of the human will be high. However, if the robot acts abnormally, the level of trust of the human will be low. In the context of HRI, it will be useful to look into this aspect and how it can also be incorporated into the current framework.

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This book consists of 18 chapters about current research results of service robots. Topics covered include various kinds of service robots, development environments, architectures of service robots, Human-Robot Interaction, networks of service robots and basic researches such as SLAM, sensor network, etc. This book has some examples of the research activities on Service Robotics going on around the globe, but many chapters in this book concern advanced research on this area and cover interesting topics. Therefore I hope that all who read this book will find lots of helpful information and be interested in Service Robotics. I am really appreciative of all authors who have invested a great deal of time to write such interesting and high quality chapters.