Resilience of a human-robot system using adjustable autonomy and human-robot collaborative control

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Abstract: Unmanned ground vehicles tend to be more and more autonomous. Nowadays, both complete teleoperation and full autonomy are not efficient enough to deal with all possible situations. To be efficient, the human-robot system must be able to anticipate, react, recover and even learn from errors of different kinds, i.e., to be resilient. Adjustable autonomy is a way to react to unplanned events and to optimise the task allocation between the human operator and the robot. It thus can be seen as a component of the resilience of a system which can be defined as the ability to maintain or recover a stable state when subject to disturbance. In this paper, adjustable autonomy and human-robot cooperation are considered as means to control the resilience. This paper then proposes an approach to design a resilient human-robot system through some defined criteria which aim at assessing the transitions of the modes of autonomy. Perspectives of this approach intend to provide metrics for the adjustment of autonomy in the most resilient way. First results from experiments achieved on a micro-world aim at a preliminary assessment of the different meanings of resilience of the system using the proposed metrics.

Keywords: human-machine systems; adjustable autonomy; resilience; affordances; human-robot interaction.

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1 Introduction

Nowadays, the breadth of missions that an autonomous mobile robot can handle increases rapidly. Designing autonomous robots allows limiting risks for the human operators by taking them away from the field of operation but it seems today essential to design systems allowing an effective human-robot interaction. Indeed, on the one hand, the difficulties of communication or the poor quality of transmitted necessary data for teleoperation make the direct remote control ineffective in some situations. On the other hand, the maturity of technology and algorithms does not allow today to design completely autonomous and sufficiently reliable robots to deal with all possible situations. A compromise has to be found between completely remote controlled robots and fully autonomous robots. This compromise consists in developing a mode of human-machine interaction aiming at optimising the use of competencies of both the human operator and the robot. Such an interaction mode is the collaborative control which has to be integrated in a system allowing a dynamic adjustment of autonomy in order to maintain a sufficient level of efficiency whatever the conditions are. Indeed, it must be taken into consideration that these unmanned ground vehicles evolve in a dynamic environment that may require an adjustable autonomy. For instance, the level of autonomy has to be raised up in case of unavailability of the human operator, due to another task-demand. This level can also be decreased when the robot is no longer able to execute a task. This adjustable autonomy is one of the possible expressions of the resilience of the system.

The first section of this paper introduces the notion of resilience, identified as the goal of the human-robot system. A first metric is proposed in this section to assess the recovery rate of the system. The second section defines the adjustable autonomy as a solution to increase the resilience of the system. In the third section, the human-robot cooperation is introduced through the human-robot collaborative control. The section devoted to the concept of affordances and its applications to mobile robotics and human-robot cooperation introduces a second metric to complete perspectives on the assessment of resilience. The last section presents preliminary results from experiments performed on a micro-world to assess the different modes of autonomy and to estimate the relevance of the proposed metrics relatively to the resilience of the system.

2 Resilience

2.1 Definitions of resilience

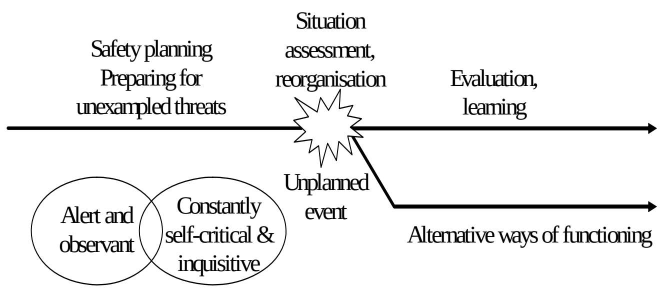
Resilience is a concept borrowed from the field of ecology and characterises natural systems that tend to maintain their integrity when subject to disturbance (Ludwig et al., 1997).

In industrial systems, resilience is related to the concept of robustness (Amalberti, 2006). Resilience is a notion that lies beyond the notion of robustness by introducing adaptation and emergence of new solutions in the functioning of the system. Emergence is thus a way for the system to adapt to perturbations, thanks to the interaction between the entities of the system.

Wreathall (2006) defines resilience as ‘the intrinsic ability of an organisation to keep or recover a stable state allowing it to continue operations after a major mishap or in presence of a continuous stress’.

Resilience can provide an interesting framework in order to design mobile robots able to recover from errors, both internal and due to the human operator. Resilience and autonomy, more especially adjustable autonomy, are related concepts. An autonomous system has to be resilient in order to adapt to unplanned events. Hollnagel (2006) introduces the notion of proactive organisation (Figure 1). Such an organisation can be applied to an autonomous mobile robot. Some metrics constantly analyse the situation to determine if the system is able to recover from any unplanned event. Thus, resilience completes the concept of robustness with the notion of proactive activity which is a way of anticipating failures. The system has also the possibility to learn from the reactions to unplanned events.

Figure 1 Resilient or proactive organisation



Source: from Hollnagel (2006)

2.2 Characteristics of resilience

Hollnagel and Woods (2006) propose some characteristics to define resilient systems. Buffering capacity is the amount of perturbation that can be absorbed by the system without a need for adaptation. Margin and tolerance define the behaviour of the system relative to a boundary of functioning. Flexibility is the ability to adapt to new constraints. Cross-scale interactions refer to the communication between the different entities of the system.

Table 1 summarises different characteristics to design a resilient human-robot system. Fiksel (2003) defines these characteristics as following. Diversity expresses the existence of multiple forms and behaviours in the system. Efficiency is the performance of the system with modest resource consumptions. Adaptability is the flexibility of the system to change in response to new pressures. Cohesion expresses the existence of unifying forms or linkages. Cohesion actually refers to the ability of the entities of the organisation to interact in order to manage perturbations.

Table 1 Characteristics of resilience

	Diversity	*Efficiency*	*Adaptability*	*Cohesion*
Human operator	Different strategies	Efficient decisions	Human adaptability	Respect of objectives
Mobile robot	Material and decisional redundancy	Efficient decisions	Adjustable autonomy	Respect of prescribed plan of action
Human-robot system	Different modes of human-robot cooperation	Efficient cooperation	Adjustable autonomy	Efficient communication

Source: adapted from Fiksel (2003)

In other terms, a system will be resilient if it is robust face to unforeseen events. These events may be technical system failures, human errors or external events coming from the environment of the human-machine system.

Resilience can be qualified as opportunities for the system to react to these unplanned events. Hollnagel and Woods (2006) state that resilience itself can not be measured, only the potential for resilience can be. Considering opportunities, a parallel can be made with the definition of human error given by Miller and Swain (1987). The authors quantify human error probability (HEP) by the following expression:

$$HEP = \frac{\text{number of errors}}{\text{number of opportunities for errors}} \quad (1)$$

In the context of a human-robot system, different kinds of recovery of errors exist: both the human operator and the robot can recover their own errors or they can both recover the errors of the other one. Thus, when an error occurs, a metric is proposed to estimate the performance of the recovery of the system (PR), i.e., the probability that the error recovery is successful (Zieba et al., 2007):

$$PR = \frac{RE_{HR} + RE_{HH} + RE_{RR} + RE_{RH}}{E_H + E_R} \quad (2)$$

where

E_H is the number of errors committed by the human operator

E_R the number of errors committed by the robot

RE_{HR} the number of errors committed by the human operator recovered by the robot

RE_{HH} the number of errors committed and recovered by the human operator

RE_{RR} the number of errors committed and recovered by the robot

RE_{RH} is the number of errors committed by the robot recovered by the human operator.

This metric focuses on the resilience seen as a way of recovering from errors of different kinds. The following section deals with another aspect of resilience, the reaction to unplanned events through the concept of adjustable autonomy.

3 Adjustable autonomy

3.1 Autonomy

A discussion about adjustable autonomy should begin with the definition of the word autonomy itself for which two main senses can be distinguished. These senses are given by the etymology of the word autonomy which is derived from the combination of two Greek words: 'autos', which means 'oneself' and 'nomos' which means 'law'. The dictionary defines autonomy as the capacity of an individual or a group to take care of itself or not to depend on an external influence. Bradshaw et al. (2004) propose two dimensions to define autonomy, namely: the descriptive dimension (actions that the robot is able to perform) and the prescriptive dimension (actions that the robot is authorised to perform).

In order to be autonomous, systems must first be automatic (Steels, 1995). It means that a system must be able to operate in an environment in order to achieve the tasks for which it was designed. In the same way, autonomous systems are able to build the laws and strategies according to which they regulate their behaviour (Smithers, 1997).

Considering these different approaches, it is interesting to define the concept of autonomy for a mobile robot following three distinct axes which take into consideration the different senses previously mentioned:

- skill, capacity and prescription of the robot to achieve a given task
- skill, capacity and prescription of the robot to decide how to achieve a task
- skill, capacity and prescription of the robot to identify and manage goal-directed constraints.

In the three axes, a distinction is made between skill, capacity and authorisation of the robot. Skill refers to the existence of technology and algorithms necessary to achieve a task. Capacity depends on the context of the mission and is likely to evolve. So, the robot may not be able to achieve a given task although it has the skill to do it. Authorisation determines if the robot is allowed to execute a certain task or to take a certain decision.

In the following section, adjustable autonomy is introduced as a way to react to the evolution of the capacities of both the human operator and the robot.

3.2 Adjustable autonomy

The concept of adjustable autonomy is close to adaptive automation (Inagaki, 2003). It establishes that functions are allocated dynamically between the human operator and the robot according to criteria related on the environment, the human operator workload and the performances of the human-machine system.

Goodrich et al. (2001) qualify adjustable autonomy as a system with several levels of autonomy and in which only the human operator has the total control of the change of level. Then, in each mode, the robot has some authority on its behaviour according to the selected mode of autonomy and the human operator can only influence the behaviour of the robot through the human-machine interface.

This definition of adjustable autonomy seems incomplete because it does not take into consideration the dynamic aspect of the situation or the operator workload which may require an adjustment of autonomy during the activity of the robot. Moreover, only the human operator is responsible for adjusting the autonomy level. This restriction does not lead to a really effective system. Indeed, if an adjustment of the autonomy level is due to the operator neglect, it is possible that this one is not available or does not have the data necessary to carry it out. The robot must thus be able to adjust itself its level of autonomy. The proposed approach for adjustable autonomy intends to build a framework taking into account the transitions between the different modes of autonomy.

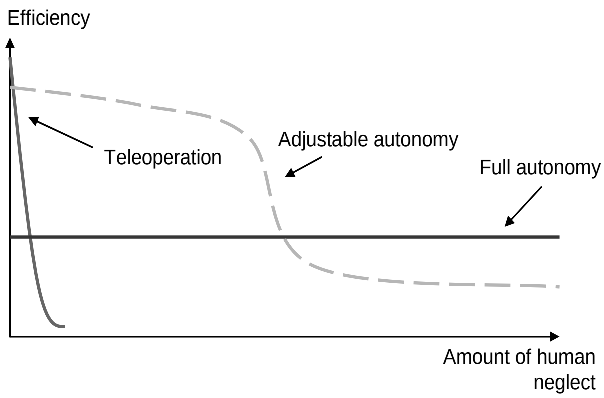
The definition we focus on considers adjustable autonomy as the property of an autonomous system to change its level of autonomy while the system operates. The human operator, another system or the autonomous system itself can adjust the autonomy level (Dorais et al., 1999). In this definition, the autonomous system represents for us the ground vehicle. The other system mentioned which can adjust the autonomy level can be compared to a calculator managing the function allocation.

Adjustable autonomy is thus a way for the system to adapt to new constraints or pressure in order to maintain a normal functioning state. It thus can be seen as a mean to control the resilience of the system.

3.3 *Adjustable autonomy and resilience*

Adjustable autonomy can be seen as a way to adapt the system to modifications in the environment in order to optimise the task allocation between the robot and the human operator.

Figure 2 Effect of the human operator neglect



Source: Goodrich et al. (2001)

One of the goals of the adjustable autonomy, if it is considered as a way of designing a resilient system, is thus to make the system more resistant to perturbations. Goodrich et al. (2001) illustrate the effect of the human operator neglect on different types of systems (Figure 2). In the case of teleoperation, the efficiency of the system is highly dependant of the human operator implication. Due to the lack of technology maturity, when the robot is fully autonomous, the system efficiency is lower than in teleoperation mode. The third solution where tasks are shared between the human operator and the robot allows having a better efficiency.

The following section introduces a proposal for the human-robot collaborative control for an adjustable autonomy. Indeed, adjustable autonomy leads the human operator and the robot to achieve together some tasks and the cohesion between them has to be assured in the transitions. In this way, the resilience of the system is maintained: the robot assisting the human operator for operational task, the human operator managing more strategic and tactical tasks. Resilience can be increased if the human operator and the robot are considered as peers, working together to achieve a common goal. Human-robot cooperation, and more precisely, human-robot collaborative control, can thus be a solution to increase the resilience of the human-machine system.

4 Collaborative control

4.1 Collaborative control and modes of autonomy

Collaborative control is close to shared control or traded control (Sheridan, 1992). Fong et al. (2003) defines collaborative control as a mode of human-machine interaction placing the human operator and the robot at the same decisional level. They are considered as partners working together to achieve a common goal. The human operator is now more a collaborator than a supervisor but the robot remains subordinate to a high-level strategy developed by this human operator. The result of a negotiation taking place in collaborative control via an interactive dialogue can be an adjustment of the autonomy of the robot, but an approach based on adjustable autonomy and collaborative control has to take into account a definition of the modes of autonomy of the system. This section introduces the modes of autonomy for the collaborative control.

Collaborative control must be designed to manage the transitions between different modes of autonomy. These transitions will result in different roles for the human operator, which require different types of information to maintain sufficient situational awareness (Scholtz, 2003).

The role of the human operator and the robot is more or less important regarding the control level. Three levels are commonly distinguished:

- The strategic level: this level concerns the long time scheduling in order to achieve global goals. Sub-goals can be formulated.
- The tactical level: this level concerns the mean-time scheduling to achieve sub-goals elaborated at the strategic level.
- The operational level: this level concerns means applied to realise the tactical requirements.

The human operator activity depends on which level he/she intervenes. Parasuraman et al. (2000) describe the activity of the human operator through four categories:

information acquisition (C0), information analysis (C1), decision-making (C2), action implementation (C3). Each category may be more or less automated.

Considering, for example, three general modes of autonomy [a manual mode (M0), a semi-autonomous mode (M1) and a fully autonomous mode (M2)], Table 2 illustrates the allocation of the categories of activity between the human operator and the robot.

Table 2 Roles of the robot and the human operator

	M0	*M1*	*M2*
C0	H	R	R
C1	H	H-R	R
C2	H	H-R	R
C3	H	R	R

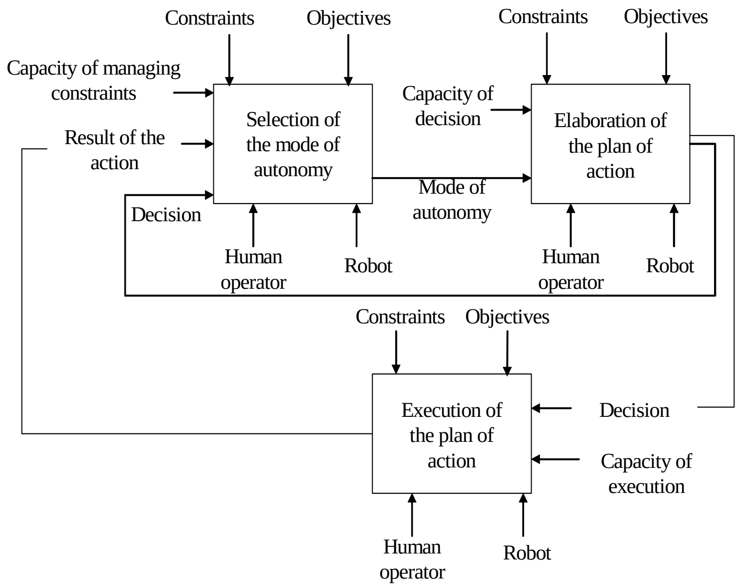
Notes: H: human operator, R: robot.

In the mode M1, information acquisition and action implementation are dedicated to the robot. In this mode, the human operator analyses the information and decides. For these two tasks the robot may assist the human operator.

These different modes of human-robot interaction contribute to the resilience of the system by introducing diversity and cohesion. The proposed approach intends to gather notions of adjustable autonomy and collaborative control in a common architecture.

Figure 3 thus illustrates a perspective of architecture for the collaborative control which integrates adjustable autonomy in order to contribute to the adaptability of the system. Collaborative control intervenes at the different stages of the architecture by involving both the human operator and the robot. Moreover, each stage of the architecture is likely to require an adjustment of the autonomy regarding the current constraints and the objectives.

Figure 3 Perspective for collaborative control



Collaborative control can thus refer to interactive redundancy which is characterised by functions of reception, transmission and interpretation. All these functions of communication intervene at the different stages of the collaborative control and are more likely to be used in the intermediate modes of autonomy where both the human operator and the robot are concerned. Indeed, in a fully autonomous mode for instance, interactions between the human operator and the robot may not be as numerous.

These functions of communication must be gathered around a common representation of the environment and the actions likely to be performed. The following section introduces such a formalism based on the concept of affordances.

5 Affordances

5.1 Definitions of affordances

The concept of affordances was first introduced by Gibson (1986) to explain what the environment offers an animal, what it provides or furnishes, either for good or ill and how it is perceived by this animal.

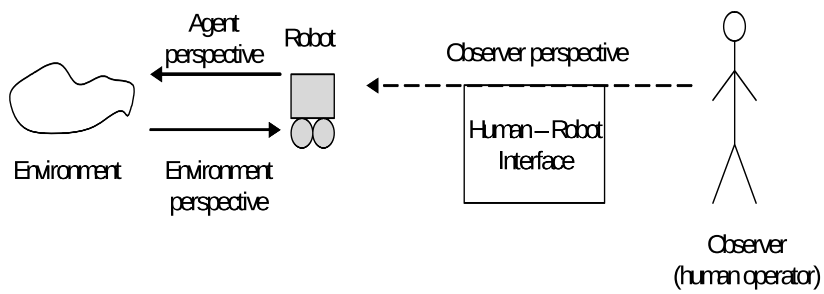
To link the concept of affordances with autonomy, autonomy may be considered as the possibility for the robot to efficiently detect affordances and successfully actualise them. Firstly, this ability to actualise affordances can correspond to the ability of the robot to perform some tasks. Moreover, Stoffregen (2003) states that ‘perceiving that a given intention cannot be satisfied here, now, can motivate an animal to seek out conditions under which the intention can be satisfied’. This can be closely related to the axis of the autonomy determining the ability of the robot to take some decisions.

Affordances can be sequential: once an affordance is actualised, other affordances are perceptible (Gaver, 1991) and effects resulting from the actualisation of affordances can thus be seen as a series of different states for the agent linked by a function applying behaviour to an element of the environment. The following section proposes formalism for such a function applied to mobile robotics.

5.2 Affordances in robotics

For a mobile robot, three points of view are possible to define affordances: from the agent, from the environment and from the observer (Sahin et al., 2006).

Figure 4 Perspectives for perceiving affordances



These three perspectives (Figure 4) can respectively be applied to mobile robotics in terms of mobile robot, environment and human operator. The point of view from the environment can be formalised although it may not be relevant in the domain of mobile robotics.

The point of view from the agent is the following one: [*effect*, (*entity*, *behaviour*)].

It can be considered as the previously mentioned function expressing the fact that when the agent applies the behaviour on an entity in the environment, an effect is generated.

The difficulty is to represent in a real and dynamic world the point of view from the environment, which is the following one: [*effect,* (*agent, behaviour*)].

An extension of this formalism considers the point of view of an exterior observer as following: [*effect,* (*agent,* (*entity, behaviour*))].

This third point of view is closely related to the context of the human operator remotely controlling the robot (i.e., the agent). Indeed, this operator, by observing the robot, can determine what affordances it can detect and establish a mental model of this robot and of its capabilities. This detection of affordances is performed in this case via the human – machine interface. In this case, perception by another agent in a dynamic context is likely to lead to errors of perception or interpretation of affordances.

Gaver (1991) introduces the notions of false and hidden affordances. Such affordances are likely to lead to erroneous errors and could be taken into account in the evaluation of the autonomy of the robot.

A link can be established between affordances, autonomy and opportunities. Affordances can provide a metric to assess the capacity of the robot to anticipate some potential erroneous situations. This metric (AR) can be defined as follows (Zieba et al., 2007):

$$AR = \frac{PA + HA + FA}{TA} \qquad (3)$$

where

PA is the number of successfully actualised perceptible affordances

HA the number of hidden affordances detected

FA the number of false affordances detected

TA the total number of affordances.

This metric allows assessing the efficiency of the system based on affordances. Efficiency is one of the characteristics of resilience and the impact of affordances on the resilience of the system is described in the next section.

5.3 *Affordances and resilience*

Table 3 applies to the concept of affordances the characteristics of resilience introduced in the previous section to present what affordances can bring to the human-robot system.

Table 3 Impact of affordances on the human-robot system

	Diversity	*Efficiency*	*Adaptability*	*Cohesion*
Human-robot system	Number of possible actions and decisions	Elimination of possible erroneous actions	Selection of appropriate solutions	Coherence between actions and objectives

In a cooperative context, information exchange is extremely important. The communication related to affording object is a means to improve the resilience of the system.

Several kinds of communication can be implemented:

- The robot sends some affordances it detected: this communication can be interpreted as an intention communication. For instance, the robot may detect a road to follow and can modify its behaviour. With this information the human operator may decide to accept or reject this intention of action, or to advise the robot that it is not a road and to avoid an erroneous perception.
- The human operator guides the perception of the robot by indicating an object present in the focus of the robot, or by asking to change observation direction.
- The human operator asks the robot to look for object implying a particular affordance, for instance an object that could be followed.
- An agent (the human operator or the robot) detects an object implying the other agent to modify its behaviour. For instance the agent detects an obstacle implying the other agent to modify the trajectory.

The design of the cooperation framework has to facilitate and to formalise these communications.

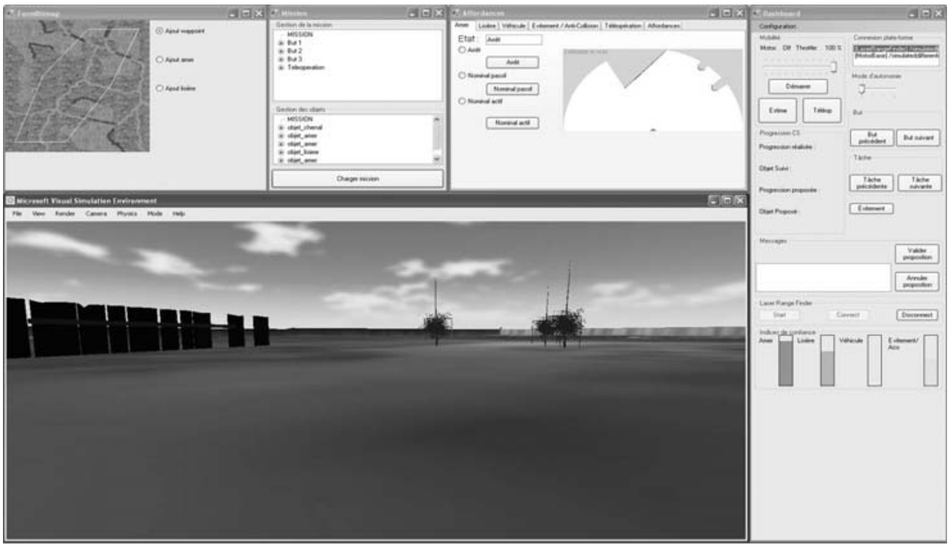
6 Validations

A micro-world was developed to assess the different modes of autonomy and the human-robot cooperation. First experiments aimed at comparing the performances in different modes of autonomy and at using the first indicators previously defined. This micro-world simulates the achievement of a mission by an unmanned ground vehicle in a natural environment (Figure 5). The human-machine interface provides the operator with information such as a map of the world, the progress of the mission, sensor data, and a simulated camera view.

Different modes of autonomy are implemented in this simulation and based on the description of the modes proposed in Section 4. A first mode consists of a teleoperation mode. A second one is a mode similar to a traded control where the robot achieves the task in an entirely autonomous way but the human operator can take control of the robot in case of a problem. In the third mode, similar to a shared control, the human operator plans the itinerary of the robot and the robot achieves the task autonomously. This last mode still includes the possibility for the operator to take control back.

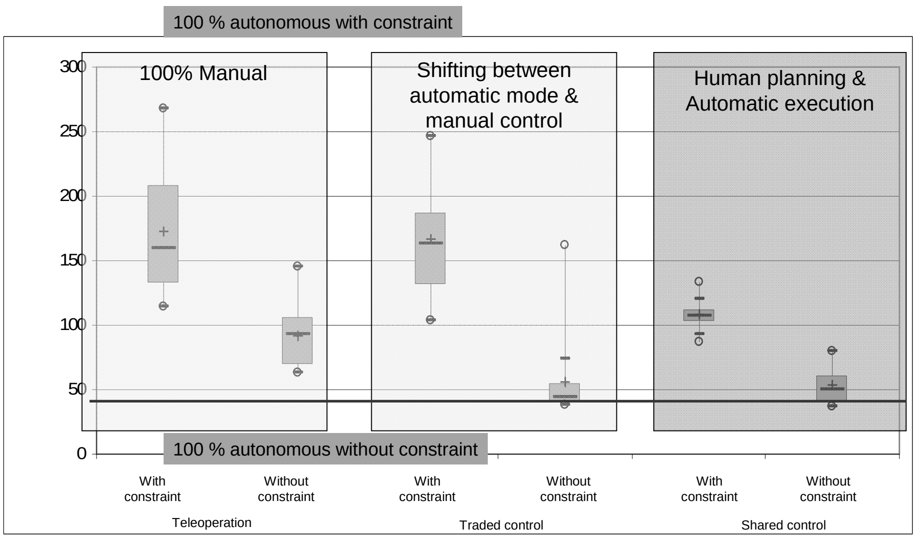
Experiments consist in reaching a goal in the virtual environment, located on a map including some obstacles. Operators have a constraint to respect for some scenarios which concerns the avoidance of obstacles. When this constraint is not mandatory, some obstacles can be crossed but it damages the robot. Different scenarios are used in these experiments. The different modes of autonomy: teleoperation, traded control and shared control are crossed with the presence or the absence of the constraint.

Figure 5 Overview of the micro-world interface



Preliminary results can be analysed relatively to the performance, i.e., the time of the mission and its variability using the different modes of autonomy. These experiments also aim at interpreting the proposed metrics of recovery rate and anticipation rate in order to provide a first assessment for resilience of the system through the different modes.

Figure 6 Variability of the performance for the duration of the mission in different modes of autonomy



First results show that variability for the duration of the mission is the most important in the teleoperation mode due to the differences between the operators. First results show that performance is increased when the human operator plans the mission of the robot and when the robot autonomously achieves this mission (Figure 6). The adjustment of constraints can also lead to best performances when using shifting between autonomous modes and manual modes, i.e., the traded control.

Teleoperation mode is the baseline for this experimental protocol which aims at a first assessment of the indicators defined in equations (2) and (3). Comparisons then focus on differences between shared control and traded control and the proposed metrics are interpreted as follows.

Computation of the metric relative to recovery of errors takes into consideration the number of transitions initiated by the human operator. These transitions actually concern a recovery of a conflict situation by the human operator. This first metric is thus assessed by computing the ratio between the number of transitions and the number of opportunities for errors.

Anticipation rate is related to the points indicated by the human operator useful to plan the mission of the robot. Anticipation may be assessed by the ratio between the number of points indicated by the human operator and the number of potential conflicts on the path of the robot. These points correspond to possible actualisations of affordances. The number of points indicated by the operator then corresponds to the number of detected affordances.

For these two metrics, the average number of opportunities for errors on the map was estimated at 35. It corresponds to the average number of transitions that are likely to be initiated by the human operator or to the average number of points that may be indicated by the operator by taking into consideration the most relevant itineraries on the map.

Traded control is more devoted to manage conflict situations by recovering errors (Table 4). Recovery rate represents 38.1% of the management of the conflict situations solved by the human operator without the constraint of avoidance. Transitions between modes of autonomy are initiated by the human operator and correspond to solutions of the human operator to manage a difficulty of the robot. In shared control, mean recovery rate appears to be very low: from 1.9% to 3.1% of the conflict situations were managed through recovery of errors by the human operator (Table 4).

Table 4 Comparison of recovery rate in different modes

	Traded control with constraint	*Traded control without constraint*	*Shared control with constraint*	*Shared control without constraint*
Mean recovery rate (%)	38.10	13.10	1.9	3.1
Standard mean deviation	19.08	12.63	2.81	0.82

Shared control is more likely to manage resilience by resorting to anticipation as 74.76% of the conflict situations were solved through anticipation (Table 5). In this kind of control, the human operator anticipates potential sources of conflict, due to difficult obstacles for instance, by placing waypoints to be followed autonomously by the robot. In shared control, the adjustment of a constraint related to the context and to the objective, allows decreasing the anticipation rate to 15.48% (Table 5) while maintaining the same performance (Figure 6). This result can be interpreted as the importance of adaptation in resilience achieved through the adjustment of the constraints.

Table 5 Comparison of anticipation rate in different modes

	Shared control with constraint	*Shared control without constraint*
Mean anticipation rate (%)	74.76	15.48
Standard mean deviation	26.15	12.27

As recovery and anticipation increase, performances increase. Comparisons between shared control and traded control show that these two aspects of resilience are used for different and complementary positions on the map. The different demands of resilience are then specific to different types of errors. First results show that control of resilience is performed through different and complementary modes of autonomy, each one being specific to one aspect of resilience. Combination of the modes of autonomy is thus a way to control resilience of the system at a larger scale, that is to say by taking into consideration anticipation and recovery.

7 Discussion and conclusions

In order to design more resilient human-robot system, indicators have to be defined. This paper proposes an indicator to assess the recovery rate of a human-robot system, which covers an aspect of resilience. This indicator takes into account the number of errors committed and recovered by the human operator and/or the robot.

In order to improve the resilience capacity, some means have to be placed. These means have to decrease opportunities of errors and to increase opportunities to recover from errors and to guide the system towards correct behaviour.

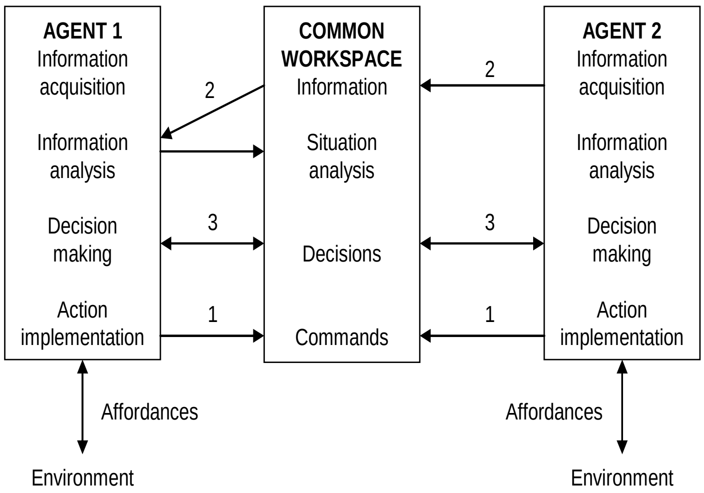
Principles of cooperation between the human operator and the robot based on adjustable autonomy are proposed as a solution to allow sharing dynamically tasks between the human operator and the robot. Regarding the capacity of agents (competences, dependability) some tasks are allocated to an agent. According to Parasuraman et al. (2000) taxonomy, tasks are classified in four main classes:

- information acquisition tasks
- information analysis tasks
- decision-making tasks
- action implementation tasks.

Autonomy modes are proposed following this classification. Dynamically and following the context, the system switches on the most appropriate mode. The recovery rate (*PR*) can be an indicator to manage this switch.

The proposed approach aims at considering adjustable autonomy as a framework in which both the human operator and the robot are taken into account for the transitions between two modes of autonomy. This relates to the property of cross-scale interactions necessary to design a resilient system which should implement the concept of common work space (Pacaux-Lemoine and Debernard, 2002) and adapt it in order to relate to the definition of the modes of autonomy and to take into account the model proposed by Parasuraman et al. (2000) (Figure 7).

Figure 7 Adaptation of common work space



The different forms of cooperation proposed in Schmidt (1991) can be found in this work space:

1 the augmentative form, to help the other agent to perform a task

2 the integrative form, to analyse a situation with information provided by another agent

3 the debative form, to confront decisions taken by the agents placed at the same decisional level in the architecture of collaborative control.

Through this work space, the adjustable autonomy framework has thus to facilitate the opportunities of an agent to supervise and to correct the other agent.

This paper proposes to base this mutual supervising on the principle of affordances. The capacity of the robot to anticipate some erroneous situations can be assessed regarding the affording capacities.

First experiments assessed these indicators by testing different modes of autonomy. Preliminary results show that a single mode of autonomy does not seem to be optimal for a given situation or even for a given operator. Performance is increased if the mode of autonomy is adjusted according to the context and to specific demands in terms of resilience. Adjustment of constraints combined with either anticipation or recovery relatively to the context allows producing best performances. Resilience of the system is thus a combination of capacities of anticipation and recovery and capacities of adaptation to the context.

Perspectives relate to communication of affordances in order to improve the situation awareness and to facilitate correction if needed. In this perspective of dialogue, a particular effort has to be done concerning the human-robot interface design by respecting ergonomics criteria. Indeed, the HMI can not lead to an increasing of the human operator workload.

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