Human-like conception of a remote control robotic system - Morphological aspects

P. Hoppenot*, Y. Rybarczyk, D. Mestre****

*LSC, University of Evry, hoppenot@iup.univ-evry.fr

**LMP, CNRS & University of Marseilles, rybar | mestre @laps.univ-mrs.fr

Abstract – In remote control situations, sensorial impoverishment is one of the main difficulties. One way to minimize its influence on the system's performance is helping the human operator to perceive and understand the remote system's behavior. This paper is based on the concept of *appropriation* of an object by a user, derived from Piaget's theory of *adaptation*. This developmental psychologist proposed that humans adapt themselves to the external world through two complementary processes: *Assimilation* corresponds to the generalization of pre-existing schemes to the use of a new device or object. *Accommodation* corresponds to the differentiation of pre-existing schemes, which leads to the development of new schemes. This theoretical framework was tentatively applied to the telemanipulation of a manipulator arm. Experiments were conducted on this device, in order to test whether the anthropomorphic aspects of the remote systems could help the operator assimilate the device into pre-existing operating modes. The outcome of this successful adaptation process would then lead to an appropriation by the operator of the remote device characteristics.

Keywords: Remote control, appropriation, robotics.

I. INTRODUCTION

The most important problem in remote control tasks arises from sensorial impoverishment, due to the separation between the entity that controls the action (the operator) and the entity that executes the operator's commands (the machine). Fig. 1 illustrates a remote control situation, in which the human operator is at distance from the area in which the action takes place.

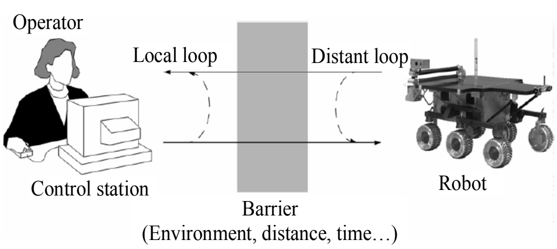

Fig. 1. Remote control situation (adapted from [FON01]).

The most common adapted solution to solve this problem is to try to optimize man-machine co-operation. Key concepts are task allocation ([GAI97]) or function allocation ([HOC00]) between man and machine. One initial idea was to compare, for a given task, the performance of man and machine, and to assign it to the agent with the best result ([FIT51]). However, several criticisms have been formulated. The main one is that, while some tasks are totally executed by the machine, the human operator still keeps responsibility for the global system. In some cases, this strategy, in which the operator is kept out of the control loop results in the abandon of automatic modes by the operator ([VAN94]). The notion of joint cognitive systems, introduced in [HOL83] and further developed in [RAS94] and [WOO95], suggests that "the system must facilitate the appropriation of the system response by the operator" ([KAR95]). So, the problem is not only that of task allocation but that of how the operator understands and masters the system's overall behavior. In normal conditions, human beings exploit a great diversity of sensorial information (visual, auditory,, tactile…). In remote control situations, some of them are degraded or totally absent. Two of them are overexploited: vision and proprioception, which a clear emphasis on the visual modality ([GRI97], [STA98]).

The present paper deals with experiments carried out using video feedback only. Piloting the displacement of a remote device with video feedback always induces a deterioration of the performance, as compared to direct control, even when the size and orientation of the perceived visual scene are not modified ([SMI90]). It is expressed by a difficulty to evaluate precisely the relative positions of elements in the scene, which affects distance evaluation. [MAS89] shows that this decrease in performance might arise from visual field restrictions. In addition, the scene is projected on a two-dimensional surface, which invalidates some depth cues, like binocular disparity and motion parallax ([CUT95], [REI96,[BIN98], [COR96]). It is also impossible to determine the distance of an object only using only its apparent size. Consequently, the reduction of visuo-spatial cues to depth perception results in a reduction of performance in remote control situations ([FER01]). These results are confirmed by psychophysical evaluations. In natural conditions, a decrease in the spatial precision of a movement is observed when this latter is executed "through" a reduced visual space ([COE97]) or a poorly structured visual space ([COE00]).

In this context, the present paper deals with the concept of appropriation, extrapolated from Piaget's theory of adaptation of a subject to the external world ([PIA36], translated in 1952 [PIA52]) and presented in section II. Section III introduces the context of disabled people assistance with its specific constraints. In section IV, the impact of morphological aspects of a remote system is studied and section V gives experimental results obtained with a real manipulator arm.

II. APPROPRIATION

Remote control situations are related to the question of appropriation of a tool, distant in this case, by the operator. The first researcher who tried to mix psychology and technology is Vygotsky ([VYG30]). He noted that the integration of an instrument into a behavioral process induces actions linked to its use and to its control. Studies by Rabardel in the context of robotics extend this approach to the re-composition of the action, following an instrumental approach to man-machine relationships ([RAB91]). An instrument is not only an object. In the one hand, it is composed of a real or symbolic artifact. In the other hand it involves schemes, which come specifically from the operator or from social schemes. In other words, a tool is not only a part of the external world but also a product of the action of the operator. However, although artifacts and schemes are associated to define an instrument, they can both be relatively independent. Indeed, one scheme can be applied to different artifacts of the same class (driving schemes for different cars) or neighboring classes (sometimes with possible dramatic consequences, for example using heating properties of microwave ovens to dry a pet). On the contrary, one artifact can be associated to different schemes for different functions. For example, a screw driver can be used to make a hole. Finally, an instrument is a stable association of an artifact and different identified schemes. Generally, artifacts exist. Schemes appear by a process of generalization of pre-existing schemes or by the construction of totally new schemes.

To understand the origin of instrument construction, it is necessary to study the concept of adaptation introduced by Piaget. According to [PIA36] (translated in 1952 [PIA52]), intelligence is first of all a question of adaptation. Two complementary processes are involved. The first one is assimilation, which consists in the generalization of pre-existing schemes. Because of an appearance proximity or a situation proximity, the use of new objects can be assimilated to pre-existing schemes. The second adaptation process (accommodation) consists in the differentiation of pre-existing schemes. The experiment presented in [PIA36] helps us understand the complementary nature of these two processes. A child is situated in front of a sofa on which a bottle is posed. The child has a stick with which he/she had learned to hit objects. First, the child tries to catch directly the bottle, which is not possible, and then begins to hit it with the stick. The bottle falls by chance. The child goes on hitting the bottle when it is on the floor. He/She observes the movement of the bottle and begins to push it with the stick to bring it towards himself/herself. Later, without a stick, he/she uses a book to bring again the bottle towards himself/herself. In this experiment, the child has first used a pre-existing scheme (hit with a stick), but such assimilation does not allow to catch the bottle. The scheme is progressively accommodated, in order to obtain the movement of the object and a new scheme: push with a stick. Then, this last one is generalized to other objects, here a book.

We suggest that Human-Machine Interaction follows the same logic. When the machine presents operating modes that are close to those of the operator, they can be directly assimilated. On the contrary, if the device is completely "different", the operator must accommodate (Fig. 2). Consequently, taking into account the gap between existing schemes and representations of the operator and the schemes and representations that are necessary to control the robot is essential to achieve a successful ergonomic conception. Two directions are possible. The first one consists in reducing the gap between the pre-existing schemes of the operator and the schemes that are relevant to control the machine, with the objective of extending the sensori-motor repertoire of the operator. In this case, the operator will try to attribute his/her characteristics to the machine ([LEO84], [GAI93]). The second direction is to take into account the gap. Ergonomic conception will then try to point it out, in order to help the operator conceptualize it. In the present study, we try to explore the first direction. Our system potentially presents physical characteristics (anthropomorphic arm, Cartesian control and video feedback) that were supposed to fit the operator's frames of reference.

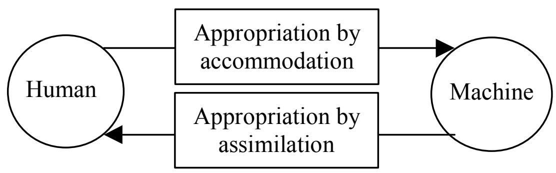

Fig. 2. Application of an adaptation piagetian model to Man-Machine Co-operation.

One major question however subsists: how is it possible to measure the appropriation of a machine by an operator?

The concept of presence, defined in the field of virtual reality, resembles appropriation by certain aspects. The sensation of "being there", in place of the avatar that represents the operator in the virtual world is one example. In [MIN80] the term tele-presence is used to describe the sensation for the operator to be physically present in the space where he/she acts via the machine. [SHE92] proposed to distinguish virtual presence for virtual reality and tele-presence for remote control situation. This separation is not useful in neuroscience [IJS00]. In fact, the central question is the mental representation of one's human body. Subjects in virtual reality situations say they were mentally more "situated" in the virtual world than in the physical world ([SLA93]). [LOO92] distinguishes between the phenomenal body and the physical body. In virtual reality situations, the mental representation of the body can be deteriorated by swapping between virtual body and physical body ([MEY92]).

In virtual reality, [IJS02] distinguishes three levels to analyze the sensation of embodiment: phenomenological, behavioral and cerebral. The last one is very difficult to measure. Phenomenological analysis takes into account rough performance of the subject. That gives information about the efficiency of the operator at piloting the system, but little information about the adaptation process. On the opposite, behavioral analysis delivers indices about movement execution characteristics and spatial representation of the man-machine system. Comparison of these data with human behavioral models favors interpretations concerning the adaptation level achieved by the operator.

III. ROBOTIC ASSISTANCE

The applied context of this paper is that of robotic assistance to disabled people. Research on robotic assistance to disabled people has been existing for twenty years. The main objective is to restore manipulation functionality to tetraplegic persons. The idea is to use a mechanical arm to palliate the deficiency of these persons. Three configurations exist. The first one consists in a fixed working station, in which a manipulator arm evolves in a structured environment. Automatic gestures corresponding to specific tasks (grasping a glass, a piece of paper from the printer…) can be pre-programmed and easily executed. This configuration has two important drawbacks. It is difficult to take into account changes in the environment and the space of intervention is limited. Two important projects have been developed in this approach. One has begun in 1985 in France: The MASTER project ([PED93]) has been extended in European TIDE project under the name of RAID (1991-1993). A commercial version exists since 2000. Another project, DEVAR, comes from the USA. The PROVAR project (1996-1999) has finalized a commercial version ([HAG99]). A third one, HANDY, is a smaller arm, developed since 1987. The initial objective is to enable a disabled person to eat and drink. Other functions have been added (makup, drawing, painting…) ([HAW97]).

The second configuration consists in embarking a manipulator arm on an electrical wheelchair. Manus® ([MAN]), developed in Holland, has been commercialized for about ten years. In is controlled through a 16-key keyboard or a joystick. Its main advantage is to be installed on the wheelchair and to follow the disabled person everywhere. Nevertheless it is sometimes difficult to use, depending on the situation (grasping an object on the floor for example). Moreover it requires the user to be on the wheelchair.

The third configuration permits to enlarge the action field of the system. A manipulator arm is embarked on a mobile base. Several projects have been developed under this idea: MoVAR ([VAN86], [VAN95]), URMAD-MOVAID ([DAR95], [DAR99], [LAS01]) and [REG92]. None of them are commercialized. This is probably due to the difficulty to have sufficient autonomous and secure systems. The key point is Human-Machine Cooperation.

LSC (Complex System Laboratory) develops the ARPH (Robotic Assistance to Person with Handicap) project since 1994. The objective is to give a degree of autonomy to disabled people in daily life. A manipulator arm is embarked on a mobile base to restore, at least partially, the manipulation function. Ultrasonic sensors are used for the displacement of the mobile base. A camera, on-board the base, delivers visual information to the user. The system is more precisely described in [HOP02].

This paper deals with a tentative human-like conception of the robot, aiming at making distant scene and distant action perception easier for the operator. Two aspects are taken into account. The morpho-functional aspect is developed for mobility (remote control of the mobile base trajectory), by implementation of visuo-motor anticipation mechanisms ([RYB04], [MES05]). The morphological aspect is tested for optimization of the manipulation function, by positioning the visual reference frame with reference to the grasping device. This second aspect is the purpose of this paper.

IV. MORPHOLOGICAL ASPECT

A. Study presentation

Space functional organization has been studied from different points of view. From a psychophysical point of view, three concentric spaces are considered around the operator. Personal space corresponds to the spatial range

in which objects can be manipulated by arm extension. Action space, about 30 meters, corresponds to a kind of relational space, in which it is possible to communicate, to move quickly from one point to another or to exchange objects. Different sources of information are used to detect space according to distance ([CUT97]).
From a neuro-psychological point of view, near space and far space are distinguished. Some pathologies have been described, in which patients differentially lack mental representations for either near or far space ([COW99]).
From a neuro-physiological point of view, studies have shown that different cerebral areas are activated, depending on whether peri-corporal or extra-corporal space is involved in the control of action ([JEA97]).

This dichotomy in two or three spaces has no precise limit. Corporal schemes result from dynamic properties. [IRI96] shows that when a monkey uses a tool, its peri-corporal space extends to the accessible space using this tool. In the case of peri-personal neglect, peri-corporal space is extended by the stick dimension ([BER00]). In a remote control situation, the intervention field of the operator increases in proportion with the mechanical tool. Following this, it might be possible to make the hypothesis that the same peri-corporal space extension of the operator will include the remote controlled robot. But another characteristic of a remote control situation is that no physical contact with the tool exists. That could disturb the visuo-tactile integration phenomenon. Indeed, previous studies have shown that there is no peri-manual space extension in the case of physical discontinuity between the operator and a stick when the relation is passive ([MAR01]). In our case, the operator is active but has no tactile feedback. It is also important to point out that perception-action relationships are more difficult in remote control situation than when the operator manipulates a simple tool. Specific sensori-motor distortions appear with 2D screen for 3D initial information ([PEN02], [PEN03]). Consequently, The very particular context of remote control operation requires a specific study of space representation modulations

B. Objectives

The objective of these experiments was to study if an anthropomorphic "camera-arm" configuration on the remote controlled robot facilitates the control of the system. To evaluate the appropriation of the robotic system the variation of the dimensionless number Π (defined below) has been studied. Two experiments have been realized. The first one compares the operator's spatial representation with the robotic arm and the human arm, taken as a reference. The second one deals with the comparison of different relative positions of the robotic arm and the camera. A third experiment analyses the motor dimension of remote control.

In [WAR87], a number Π is defined to characterize the ratio between a dimension of the human organism and an experimental environmental variable associated to it. It is then possible to identify optimal rations, for which actions will be easier or efficient and, in the opposite, critical ratios for which actions will be more difficult to carry out. In the following experiments, objects to catch are at a distance D which is compared with the length of the robotic arm, R. In this case, $\Pi=D/R$. If D exceeds R, it is impossible to catch the object. Π not only measures a simple geometrical space perception but also spatial representational capacities of the operator. Indeed, to estimate the distance for which the object is not reachable, the operator must transform absolute co-ordinates of the environment into relative coordinates referenced to the arm ([FIT78]).
In the present experiments, D represents the estimation by the human operator of the maximum distance of an object, which can be taken and R is the effective length of the arm. Then the more Π tends towards 1, the more the operator can be assumed to possess an accurate representation of his/her operation field, hence a a good representation of his/her corporal scheme. In the first experiment, two conditions are compared: robotic arm and human arm. In the second experiment, only the robotic arm is used and variations of Π are computed with different relative positions of the camera and the arm.

The third experiment deals with another criterion. Indeed, [PAG98] shows that there is no correlation between a verbal judgment and a "motor" judgment of distance perception, in monocular vision. It is thus important to measure motor control, in order to appreciate the real appropriation level of the system by the human operator. To evaluate this motor dimension of remote control, different types of parameters can be used. [VIV91] classifies them into two levels of analysis: phenomenological and behavioral. The first level deals with simple performance evaluation. We have chosen two phenomenological parameters. The success rate corresponds to the ratio between the number of times the operator actually grasps the object and the total number of trials. The second parameter is the mean execution time of a movement. The behavioral level consists in a comparison with a model. Once again, two criteria are evaluated. The first one, inspired by [MAG92], measures a spatial error (S), defined by the deviation of the real trajectory from the ideal one. In fact, this error corresponds to the ratio between the distance covered by the robot (R) and the theoretical shortest distance (T): $S=R/T$. The second criterion concerns the co-ordination between the movement of the arm and the opening of the grip. [JEA84] gives two criteria to measure this co-ordination. The first one establishes a link between co-ordination and synchronization in cinematic changes of arm movement and grip opening. The number of simultaneous occurrences expresses the appropriation level. The second criterion is the time of the beginning of the opening of the grip. [JEA84] shows that the opening of the hand is initiated at the beginning of the arm movement, which reveals a clear anticipation of the grasping of the object.

V. EXPERIMENTAL RESULTS

A. Appropriation evaluation

In fact, the issue is to compare R and the maximal catching distance D_m evaluated by the operator. The closer $\Pi_m=D_m/R$ is to 1, the more the appropriation is claimed to be effective. R is easy to estimate. For D_m, it is more difficult. 8 positions are defined according to R. 4 are lower than R, 4 are higher than R: ±1cm, ±4cm, ±8cm, ±13cm. The subject must answer "yes" or "no" to the following question: "Can you catch the object with a simple arm extension?". To obtain the threshold value, each position is proposed 10 times in the five directions (Fig. 3). Once the 80 responses are recorded, the threshold S corresponds to the same number of "yes" and "no" on each side of S ([BON86]).

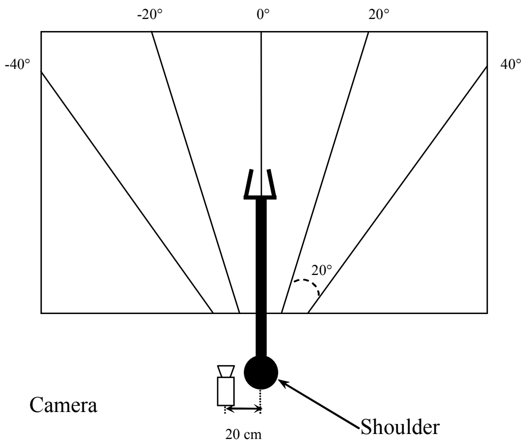

Fig. 3. Experimental device characteristics in the first experiment

Two experimental configurations are tested. In remote control conditions, the camera is situated on the left of the mechanical arm, which corresponds to a right anthropomorphic condition. Operators have only indirect information of the scene through camera feedback. In natural conditions, operators are located at the exact position of the robotic The first major result of this experiment is that there is no significant difference between remote control and natural conditions. Moreover, such accurate spatial representation in remote control conditions is acquired very quickly, suggesting that the reorganization of space representation is possible without extensive use of the tool ([BER00], [MAR01]).

With a more precise analysis, direction by direction, a second result appears. In two directions, 0° and 20°, Π_m is lower than 1 in the robotic condition and nearly equals to 1 in the natural condition. Two interpretations are possible: Either the subject has over-estimated the distances or the length of the arm was underestimated. Several works have shown a tendency to underestimation of distances by subjects in monocular or limited field vision ([CRA70], [MOR84], [SER92], [BIN98], [COE97]). [FOG96] shows that peri-personal space is similar to circular or spherical arcs around the considered organ. But, contrarily to human arm, Manus® arm, used in this experiment, presents a more important extension radius in 0° direction than on the sides. This bias explains Π_m variations. If only the numerator of Π_m is taken into account, the representation of extension space of the arm tends towards a circle like human arm. We can deduce that the operator had transposed her/his own arm representation onto the robotic arm.

This experiment shows that an anthropomorphic position of the camera, according to the arm, results in the fact that space representation in the remote control situation is similar to that in the natural situation.

B. Relative positions between robotic arm and camera

The previous experiment's results show evident signs of appropriation of the remote control system by the operator when its configuration is defined following an anthropomorphic relative position between the arm and the camera. The question is now to test whether appropriation is also possible without an anthropomorphic configuration. Experimental conditions in this case correspond to a progressive deformation of the camera-arm configuration from an anthropomorphic one to one in which the camera positioned at 90° relative to the arm, with an intermediate "bias" configuration, in which the camera is positioned at 45° (Fig. 4).

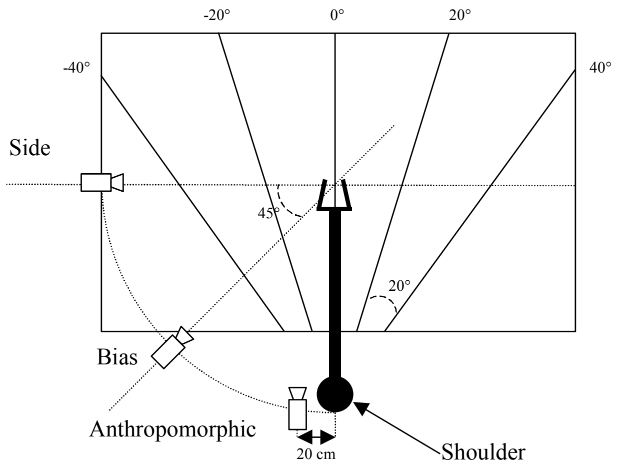

Fig. 4. Experimental device characteristics in the second experiment

First, results show that only the anthropomorphic and bias conditions give a precision in grasping space delimitation that is not significantly different from that observed in the "human" condition. It is also interesting to point out that the standard deviation in the bias condition (0.1) is nearly twice as large as the standard deviation in the anthropomorphic condition (0.06). Moreover, Fig. 5 reveals that the number Π increases when the camera moves away from the anthropomorphic condition.

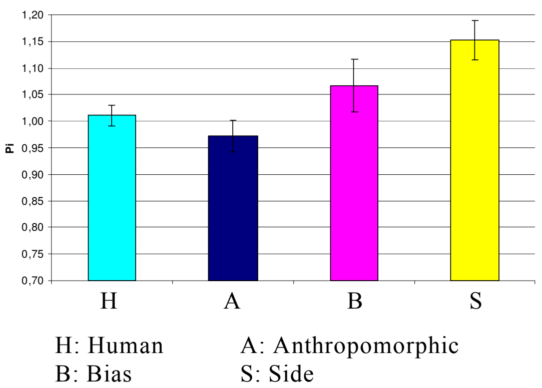

Fig. 5. Π values for distance evaluation in all conditions.

C. Analysis of motor behavior in remote control

In the last experiment, characteristics of the experimental device are the same as in the second experiment. Concerning phenomenological criteria, the analysis of success rate first reveals a session effect for all three conditions. This effect indicates a progressive adaptation of the operator to the system. Secondly, success rate is significantly higher in anthropomorphic conditions than in the other two. Thirdly, a direction effect is observed for bias and side conditions with a higher success rate in central directions (-20°, 0° and 20°). However, in anthropomorphic condition success rate in uniformly high in all directions. The analysis of mean execution time gives similar results (session and direction effects), but movement in the anthropomorphic condition is significantly quicker only when compared to the side condition.

Concerning behavioral criteria, spatial error depends on sessions. Grip trajectories are significantly more linear in the anthropomorphic condition than in the side condition, but not different from that observed in the bias condition. Fig. 6 shows that the direction effect is significant for bias and side conditions but not for the anthropomorphic condition.

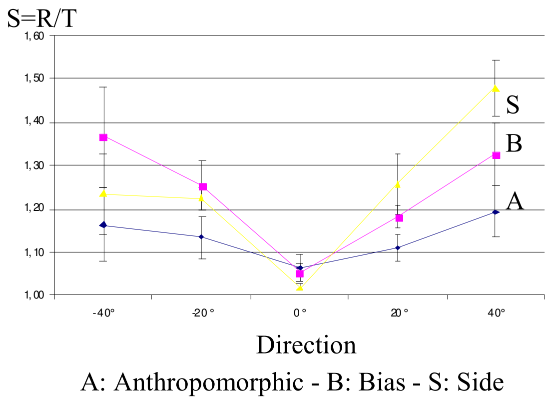

Fig. 6. Spatial error as a function of direction for the three conditions in the third experiment.

Concerning motor co-ordination, the percentage of simultaneous control of grip opening and arm movement increases with sessions. Coordination is better in the anthropomorphic condition, as compared to the side condition, but not significantly better than that observed in the bias condition. Once again, the direction effect is significant for side and bias conditions but not for anthropomorphic conditions. Grip opening gives the same pattern of results.

VI. CONCLUSIONS AND PERSPECTIVES

Optimal remote control of an external device is related to an appropriation of the device by the operator, resulting from a successful adaptation of the operator's control schemes to the characterisctics of the external system.. [PIA36] has developed a theory proposing two modes of adaptation : assimilation and accommodation. If the remote system has anthropomorphic characteristics, assimilation should be the preferential mode for its appropriation by the operator.

In the case of a robotic arm with video feedback, the question was to choose the relative position between the camera and the arm. In the first experiment, the idea was to compare the natural human corporal scheme and the corporal scheme including the remote controlled arm. When the relative position of the arm and the camera respects an anthropomorphic relation, the absence of significant difference in the delimitation of corporal space between a natural condition and a condition including the remote controlled arm constitutes a strong argument in favor of the integration of the device into the corporal scheme of the operator. The second experiment compared different relative positions of the camera and the arm, from anthropomorphic to non-anthropomorphic. Results show that the more the configuration is far from anthropomorphic, the more the precision of peri-corporal space decreases. Those two experiments dealt with high level (cognitive) signs of appropriation. The last experiment proposed an analysis at the sensori-motor level of remote control. Results show that motor performances are better in the anthropomorphic condition than in other ones.

The anthropomorphic aspect of a remote control system is a determining factor for human appropriation of the system. This result is especially important in the case of disabled people whose handicap leads to specific difficulties of world representation. Works in progress deal with automatic grasping. The idea is to add a camera on the grip. This configuration can not be compared to an anthropomorphic one. Feedback information to the user will be studied and designed to obtain a good appropriation of the system by the operator. The same line of reasoning will be applied in future experiments, using similar indices of appropriation.

In this study, only visual feedback has been taken into account, being the main source of information used in remote control situations. However, proprioceptive feedback is also extensively used in remote control situations. Recent works on haptic feedback are in progress ([COI02], [DUR03]). This approach has two advantages. Firstly, it uses another sensorial vector than video. We can assume that combining two sensorial vectors gives the operator richer information about the environment. Secondly, we suggest that haptic feedback works in a reflex-like manner, whereas video feedback involves cognitive mechanisms of higher level. With telemeters on the grip, the distance to the object can be sent back through force feedback joystick. That might also lead to appropriation, while maximizing assimilation processes.

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