A biological model for the evaluation of human-machine adaptation

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The required objective for the design of a machine to be used by a human operator is its adaptation to the user's capabilities. According to this logic, the ideal system should perfectly fit into the human sensori-motor loop. The system would disappear from the field of consciousness and the operator would use it as a "natural" extension to his/her own body.

The present study investigates a method based on biological models proposed for the control of action. We tried to evaluate whether an operator, remotely controlling the displacements of a mobile robotic device, is able to integrate the dynamical properties of the robot into his/her sensori-motor schema. The study was based on the "power law" model, linking the geometry and kinematics of a movement. The results show that the nature of the human-machine adaptation depends upon temporal aspects of the linkage between the robot's "vision" and "locomotion".

Key Words: teleoperation, biorobotics, adaptation, ergonomics, human-centered system.

1. Introduction

1.1. The problem of the adaptation of a teleoperator to a mobile robot

A person having to remotely control a mobile robot is in a peculiar sensorimotor control situation. First, he/she does not act directly on the environment, but via the remote system and command interfaces. Secondly, the information feedback is indirect through sensorial interfaces (sound, vision, haptic stimulation [1]. The presence of this spatial and temporal gap between the "master" entity and the "execution" entity generates sensory impoverishment that may be harmful for the correct achievement of the task. In the visual modality, for example, the limitations are important [2]. They relate to the reduction in the size of the visual field caused by the properties of camera lenses. A difficulty in perceiving depth is caused by an absence of binocular vision. Latencies in the visual feedback from the operator's actions are due to the mechanical loop, but also to delays in the transmission of video images. Another sensorial modality that is very sensitive to the conditions of teleoperation is proprioception [3]. Unlike in a natural situation, the operator does not (most of the time) have access to force feedback from his/her interaction with environmental objects. When haptic information is present, its "quality" is often quite poor, as compared with the situation where the operator is in real contact with the environment. The outcome is, for instance, that the discrimination of fine variations of texture and the perception of the resistance of surfaces to imposed deformation will be less based on somato-sensorial than visual cues, which might result in a saturation (in information capacity terms) of the visual channel [4]. It is necessary to note, also, that beyond the fact that most sensorial information is retransmitted in a degraded way, some modalities may even be completely absent, like sound or vestibular information.

The final major characteristic of a teleoperation task is related to the characteristics of the involved motor control. Actions which are, usually, naturally automated by the individual will require (in the teleoperated situation) the simultaneous manipulation of buttons, with a number of possible combinations. Moreover, significant temporal lag may happen between the execution of a command and the resulting movement of the robot. These delays are often associated with trajectories of the machine that obey to specific (mechanically and/or logically) rules that might strongly disturb the operator [5]. Finally, despite the importance of the multiple constraints which has been just exposed, these latter do not constitute an exhaustive list of the difficulties that are related to the remote control of a mobile robot. They just suggest the potential difficulty of the adaptation of the operator to a new situation. Thus, a condition of teleoperation and even, more generally, of human-machine interaction naturally poses the question of the adaptation of the user to his "tool".

One of the specificities of humans is their ability to get adapted to unnatural situations. As a consequence, we tend to believe that this state of adaptation can always be reached, whatever the degree of incongruity with which the individual is confronted. In fact, the tentative adaptation to a new situation requires the formation of sensori-motor schemas, that can be complex and not necessarily lead to a successful adaptation. These behavioral schemes [6] constitute a structured whole of the "generalizable" characteristics of the action, which make it possible to repeat the same action or to apply it to new contents. Thus, same schemes can be used for different situations. Concretely, by their proximity of appearance or functioning, new objects can be assimilated to pre-existent schemes. So, this tendency of a behavioral control to be preserved is defined as a process of assimilation [6]. However, when external constraint do not allow a "direct" assimilation, a second process, by which an individual manages to get adapted to a new situation occurs: accommodation [6]. It is the case, for example, when a person is confronted to a system that presents an extremely non-natural operating mode, as compared to "natural" human action control modes. In such a situation, the operator will not be able to generalize preexistent behavioral schemes, but will have to rely on an accommodation process, in order to adapt the schemes to the operational singularities of the system.

Thus, unlike the assimilation process, the accommodation process implies the creation of new sensorimotor schemes, as regards the acquisition of a new motor skill [7]. Moreover, there is no a priori guarantee that such process leads to success. Finally, such process requires a relatively time of training. Also, the many disadvantages associated with an accommodation process do not tend to privilege this type of adaptation process. Indeed, generally, it is preferable to put the individual in a situation with an assimilative dominance. It is there important to specify what we mean by "dominance". Any new situation implies processes of assimilation and accommodation. In other words, it does not make sense to think that it is possible to adapt to a new system using only a process of assimilation. Having said that, if it appears more relevant that the operator uses mainly assimilation, the delicate problem remains to demonstrate that the operator is engaged in an adaptive process with an assimilation dominance. Indeed, if it is relatively easy to quantify the performance level of an operator (time of execution of a task for instance), it is much more difficult to evaluate the type of process that is involved in the execution of a task. It is there necessary to rely on an analysis that is not limited to the performance level, but that scrutinizes the control mechanisms level. It is the reason why this article proposes a method based on the biological laws that govern human behavior in natural situation, in order to define a reliable evaluation of the adaptation level of a remote mobile device by an operator.

1.2. A behavioral model for the evaluation of assimilation: the power law

The advantage of using behavioral models is that they are the only ones that inform us, with a high degree of accuracy, about the process by which the individual gets adapted to a machine. On the contrary, a parameter such as the execution time of the task is too relative to indicate if the operator has really assimilated the system. Performance analysis at best enables us to compare an experimental condition with another, in order to determine which one provides the operator the best performance. Testing the presence of a biological law in the action control process enables us to check that the operator uses sensorimotor schemes that are similar to the ones that are used in natural conditions. Besides, number of these laws have mathematical formulations, which confers them perfectly exploitable properties, in terms of evaluation, both quantitatively and qualitatively.

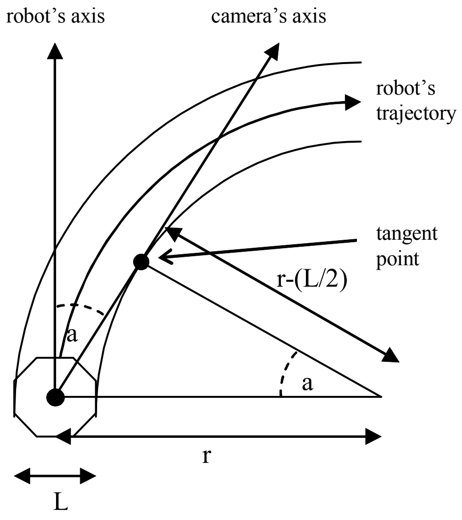
In the case of a displacement control task, there is a law, defining the spatial properties of a trajectory, that is indicated to account for the type of scheme underlying the control of the action. This law is known under the name of "power law" [8] [9]. This law defines the particular relationships between the geometry and kinematics of a "human-made" trajectory. Precisely, it shows that the angular velocity of the end of an effector is proportional to the two-thirds root of its trajectory curve, or equivalently that the instantaneous tangential velocity is proportional to the third root of the radius of curvature. This means that, during writing, for example, the velocity of the pencil decreases in curved parts of the trajectory and increases when the trajectory becomes straighter. The neuronal origins of this law remain largely unknown. However, it is remarkable that this law seems to control not only the generation of arm movements but also human locomotion [10]. Thus, the conservation of this ratio of one-third power between the radius of curvature and the tangential velocity of the movement seems to constitute a robust index of fundamental characteristics of the human sensorimotor schemes, in the domain of trajectory formation and control. In that, it represents a completely relevant behavioral model to inform us about the nature of human-machine interaction. Our hypothesis is that, if the operator, when controlling a mobile robotic device, reproduces a speed/curve relationship respecting the "power law", we can reasonably think that the conservation of this law is an indicator of the conservation of "natural" human action control schemes, further indicating a successful adaptation with an assimilative predominance. On the contrary, if this law is not found when the operator controls the robot, that suggests either that the human-machine adaptation was not successful, or that the adaptation was carried out by processes with an accommodative predominance.

In the present study of a mobile robot teleoperation, we analyzed basic performance parameters, as well as spatio-temporal characteristics of trajectories. We compared different conditions of implementation of visuo-motor coupling, with reference to observations of human sensori-motor behavior during locomotion control.

2. Experimental study: visuo-motor coupling during remote trajectory control

As indicated before, teleoperation is a situation characterized by the deterioration or absence of many sensorimotor contingencies, in comparison with natural conditions. However, one sensorial modality that is still present, and thus overexploited, is vision [4]. One consequence is that any degradation of visual information and feedback will have serious consequences for the quality of robot control. Conversely, the control of the machine displacement can be strongly improved by the "quality" of visual information. In teleoperation, the visual limitations are mainly related to the important reduction of the visual field size and to the transmission delay of images [11]. In fact, these constraints are associated with spatio-temporal characteristics of human visual perception. One strategy that has developed during evolution to cope with limited bandwidth problems is visuo-motor anticipation. This strategy consists in directing the gaze to a place in space, which is a goal or sub-goal of displacement, before actually moving the body in that direction. For example, during the control of locomotion around corners, the subject does not preserve his/her gaze axis rigorously aligned with the rest of the body, but directs this one towards the inside of the trajectory [12]. Thus, gaze orientation would anticipate displacement orientation, by systematically anticipating the changes in the direction of locomotion by a temporal interval of about one second. A control strategy following an organization of the type "I go where I look" and not "I look where I go", seems to underlie the guidance of locomotion [13]. The same thing occurs for the bypassing of a reference mark. The gaze and body movements' recordings show that the gaze is directed to the reference mark before the individual reaches its level, the realignment of the head in the direction of walk being carried out only after its crossing [14]. This suggests that gaze orientation is controlled step by step according to a predictive mechanism of the new direction to follow.

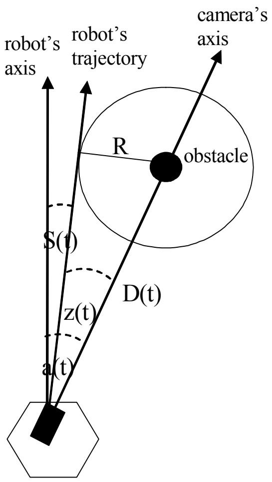
Such observations were also collected in the case of automobile control. Under these conditions, the driver's gaze axis is directed to the tangent point of the curve one to two seconds before reaching the convexity of the curve [15]. By this strategy the driver seeks to use the particular optical properties of the tangent to the turn, in order to guide the trajectory. The tangent point corresponds to a singularity in the optic flow field, being motionless when the driver's trajectory is aligned with the road's curvature. Psychophysical studies show that this gazing strategy corresponds to an optimization of information pick-up for the control of the trajectory [16]. As a consequence, it seems that this visual anticipation behavior is useful for trajectory control. We implemented this type of behavior on a teleoperated mobile robot, in order to test whether this could help human-machine cooperation. The expected result was a facilitation of the navigation control of the robot, following the example of human locomotion supported by predictive properties of the brain.



$$\boxed{a = \arccos(1-((L/2)/r))}$$

Fig. 1. Implementation of visuo-motor anticipation according to a non-human-like model. The camera's rotation angle is computed by the curve radius (r) of the robot's trajectory, using trigonometric laws. Here, cos a=(r(L/2))/r, where the semi-width of the robot equals L/2. The radius (r) is obtained by dividing the translation velocity by the rotation velocity of the robot.

First, an analogy was made between the human gaze during locomotion control and the mobile camera on the mobile robot. According to the functional architecture of our system, two possibilities of implementing a visual anticipation on displacement were available: (i) by automation of the anticipatory movement of the camera according to the navigation commands that the operator transmits to the robot (fig. 1) or (ii) by automation of the robot navigation following the commands that the operator sends to the camera (fig. 2). These two methods of camera-robot coupling differ mainly by their similitude to human behavior. Indeed, whereas the second rather scrupulously reproduces the spatio-temporal architecture of visuo-motor anticipatory mechanisms in human locomotion, the first one does not respect the temporal order of the human model.



$$\boxed{S(t) = a(t)-\text{arc sin }(R/D(t))}$$

Fig. 2. Implementation of visuo-motor anticipation according to a human-like model. The robot's navigation angle (S) is defined as the difference between the angle (a), between the camera's direction and the heading of the robot, and the angle (z), between the camera's direction and the tangent to the orbit of safety (R). This angle z is calculated by using trigonometric rules in a way that $\sin z(t) = R / D(t)$. D, the distance between the robot and the landmark, is obtained by the ratio of the rate of change of the camera angle to velocity, such as $D = (v / (da / dt)) \sin a$.

The goal of this study was finally to know whether the implementation of a visuo-motor anticipation built according to a human-like spatio-temporal architecture versus a non-human-like spatio-temporal architecture would influence the nature of the operator's adaptation to the machine. Our assumption was that, when the visuo-motor coupling follows the human model, the operator would adapt to the system by a process with an assimilative dominance. On the contrary, the adaptation should require more accommodation with a non-human like implementation.

2.1. Material and method

The telerobotic system was composed of two principal elements: a mobile platform and a control station. The robotic platform was equipped with a mobile camera. The robot was moved by two independent driving wheels, a free wheel in front of the vehicle allowing its stability. The engines were of the same type as those which equip electric wheelchairs. The optical camera field of view was 50° in the horizontal and 38° in the vertical dimension. This sensor "sent" to the operator an image of the environment in which the robot evolved, on a terminal display having a height of 23 cm and a width of 31 cm. The whole system, engines and sensors, was controlled by a PC embarked on the robot. This PC was connected to the computer of the control station through a TCP/IP HF connection. Client/server software architecture structured the informatics part. The control interface was using the PC keyboard, by which the operator controlled the direction and displacement velocity of the platform.

Three independent groups of seven subjects carried out one of three experimental conditions of visuo-motor anticipation. The first situation is was a "control" condition, in which there was no anticipation, since the camera was motionless, aligned with the orientation of the robot. In the second condition, called "non-human", the camera followed the platform displacement. The third condition, called "human-like", was a condition where the operator controlled actively the camera orientation (the robot following the camera's orientation). In the three cases, the subjects were placed in a teleoperated situation, i.e. they only had an indirect vision of the experimental environment. The task of the subjects consisted in making the robot a slalom course between four boundary marks. The instruction given to them was to carry out the course as soon as fast as possible without colliding with the boundary marks. The analysis of the results was carried out on two parameters: the path execution time and the relationship between the geometry and the kinematics of the robot's trajectory.

This last parameter was obtained by calculating the curve radii and tangential velocities of the various trajectories. After a logarithmic transformation, the correlation coefficient as well as the slope of the regression line between these two values were analyzed statistically. The curve radii and tangential velocities were standardized for each test and were represented according to the condition of vision.

2.2. Results

With regard to the performance parameter, fig. 3 shows that the subjects were significantly faster when the camera was coupled to the displacement ("not-human" and "human-like" models) than when the camera was fixed (F[2,18]=7.28 ; $p<.005$). On the other hand, the execution time of the course was not statistically different when the orientation of the camera was automated, or when this one was actively controlled by the operator (F[1,12]=0.28 ; N.S).

However, in the case of the "non-human" anticipation mode, we did not observe a statistically significant correlation between tangential velocities and curve radii (R=0.16 ;

N.S). Moreover, the regression line between curve radii and velocities has a slope that is far from the 1/3 ratio (t=7.02 ; p<.0004 for ddl=6), approaching a zero value (fig. 4).

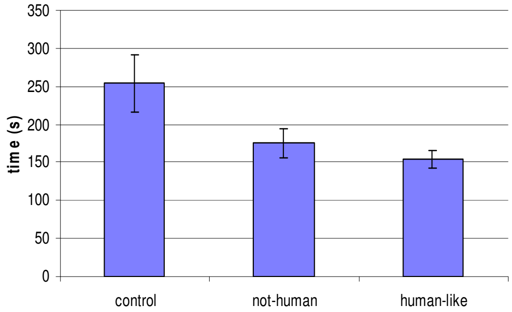


Fig. 3. The average time of execution of the travel according to the presence, or not, and the nature of the visual anticipation on the displacement.

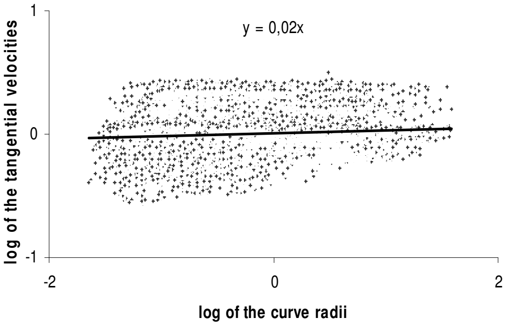


Fig. 4. Logarithmic and standardized representation of the relationship between curve radii and tangential velocities for the unit of the tests in the "non-human" anticipation condition.

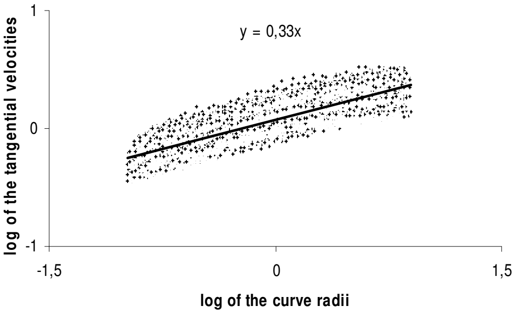


Fig. 5. Logarithmic and standardized representation of the relationship between curve radii and tangential velocities for the unit of the tests in the "human-like" anticipation condition.

On the contrary, when the operator controls a robot implementing a "human-like" visual anticipation, tangential velocities of displacement and curve radii are significantly correlated (R=0.76 ; p<.001). Fig. 5 shows clearly that, as the radius increases, velocity rises proportionally. Most remarkable is the fact that the slope of the pattern obtained does not differ statistically from the 1/3 ratio for the totality of the subjects in this condition (t=0.12 ; N.S for ddl=6).

3. Conclusions

This study shows that it is more informative to use biological laws to evaluate the level of human-machine adaptation than to use simple performance. Such behavioral models indicate in a powerful way whether the operator managed to adapt to the system, and by which process. It results from this approach an economy in the number of parameters to be used and a greater reliability of the evaluation.

Here, we saw that when the mechanism implemented on the robot follows a human model, the operator tends to an adaptation with an assimilative dominance. Nevertheless, that does not mean that the subject does not manage to adapt when the mechanism is structured in a "non-human" way. The fact that the subjects of this latter condition reach a performance level close to that observed with the "human-like" condition is a positive sign of successful adaptation. However, when the model is near to the space-time architecture of the human motor program, the operator seems to assimilate the operating mode of the machine in his initial schemes [7]. In this way, the biological law confirms its universal utility, since it not only accounts for effectiveness, but also for the limitations in the workload necessary to the control of a system; these variables representing the two pillars of the ergonomic evaluation.

A counterargument might however be opposed to our method. Because of specific properties of certain devices, it might be that a "human-like" biological law can not be found. Also, it is important to stress that through this form of evaluation, it is by no means certain that the non-reproduction of biological laws implies a non- adaptation.

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