Effect of the Implementation of the Two-Third Power Law in Teleoperation

Yves Rybarczyk and Diogo Carvalho

Abstract This research consists in studying the effect of the implementation of a biological law on the teleoperation of a mobile robot. Two experimental conditions are compared: a Manual one, in which the velocity of the robot is controlled by the human operator, and a Biological one, in which the vehicle's speed is automatically calculated by using the 2/3 Power Law. Results show that the robot is driven faster and safer with the human-like behavior than without. The objective of the study is to propose an innovative method for the development of semi-autonomous vehicles, which is based on an anthropomorphic approach.

Keywords Human-like behaviors · 2/3 power law · Remote control · Robotics

1 Introduction

The remote control of a robot implicates several constraints for the teleoperator. Ones are related to the increase of mental workload caused by the difficulties to acquire new motor schemes adapted to the control interface of the artefact. Another is the low quality of the sensorial feedbacks provided to the operator, which can be a limitation in terms of field of view, delay in the system response, absence of certain sensorial information (e.g., proprioception, audition…), among others. An

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original approach to reduce the gap between the user and the telerobot is to implement human-like behaviors in the robot's way of working [1–3]. For instance, a human behavior that was successfully modelled and implemented on a remote controlled mobile robot was the visuo-motor anticipation over the locomotion, in which the direction of the robot's pan-tilt camera was automatically oriented toward the tangent-point of the inside curve of the path, as walkers/cyclists/drivers do. Recently, [4] have shown that such an implementation enables the teleoperator to steer the machine with a significantly higher trajectory smoothness. In the present paper, we propose to study if the anthropomorphic approach can be generalized to other sensorimotor properties. A fundamental one is the fact that the kinematic of many different human movements seems to follow a same mathematical equation known as the "Two-Third Power Law" [5, 6]. So, whether the action is writing [7] or walking [8], an identical constraint relationship between the velocity and the curvature of the motor trajectory is involved. This law states that the angular velocity of the end effector is proportional to the two-thirds root of its curvature or, equivalently, that the instantaneous tangential velocity (v_t) is proportional to the third root of the radius of curvature (r_t):

$$v_{(t)} = kr_{(t)}^{-1/3}. \quad (1)$$

In other words, it means that the velocity of the movement decreases in the highly curved parts of the trajectory and increases when the trajectory becomes straighter. Here, an experiment was designed to compare the remote control of a robot with the "Two-Third Power Law" (Biological condition) versus without this human-like law (Manual condition). In the Biological situation the robot's velocity is automatically servo-controlled by the robot's trajectory according to the Power Law equation, whereas in the Manual situation the individual has to control the direction and velocity manually. The hypothesis is that a semi-autonomous driving in which the velocity is automatically set according to the Power Law principles (Biologic mode) should provide to the user a faster and safer control on the robot than a fully manual remote control of the vehicle (Manual mode).

The first part of the article explains the system developed to carry out the experiment. Then, each of the main experimental condition (Manual vs. Biologic) are described in details. After that, the experimental protocol is presented. The results of the performance for each condition are statistically analyzed. Finally, data are discussed and interpreted in order to draw some conclusions and perspectives of application in the field of the development of semi-autonomous vehicles.

2 Materials and Methods

2.1 Technological Implementation

System's Architecture. The system is composed by three main elements, which are: a remote control based on an Android mobile device, a NXT robot, and an IP camera. A wireless communication between these elements is justified by the fact that the experiment is carried out in teleoperation conditions (visual feedback mediated through a computer screen). The three components are connected in two distinct ways. The Android device communicates with the robot through a Bluetooth technology and is connected to the camera through a Wi-Fi communication. The connection between the robot and the IP camera is carried out through a support library, in order to enables a system integration between the camera and the robot. So, the users interact with the whole system through the Android remote control device, which enables them to steer the robot and receive a visual feedback from the robot's camera. An Android application was developed to allow such an interaction through a tactile user interface. The touchscreen enables the user to control the robot's trajectory, to select the steering mode of the vehicle (Manual vs. Biologic), to calibrate the IP camera, to connect and disconnect the system. Figure 1 exhibits the architecture and the technologies used to interconnect the main components of the system.

Robot's Behavior. The robot is built on four wheels, with two front-wheel-drive (Fig. 2, on the left). Each wheel-drive is controlled by an independent engine. The differential of velocity between the left and right wheel rotation enables the robot to change its direction. The IP camera is set on a mobile support, which is controlled by a third motor. The camera's orientation is automatically calculated according to the direction of the vehicle, in order to point toward the inside of the trajectory. Consequently, the pan camera provides to the user a visual anticipation over the vehicle's locomotion, because any change of direction is synchronized with a camera's rotation proportional to the curvature of the robot's trajectory. This

Fig. 1 Diagram of the architecture that represents the main elements of the system (user, remote control, mobile robot and IP camera) and the technologies used to ensure the communication between them (Wi-Fi and Bluetooth)

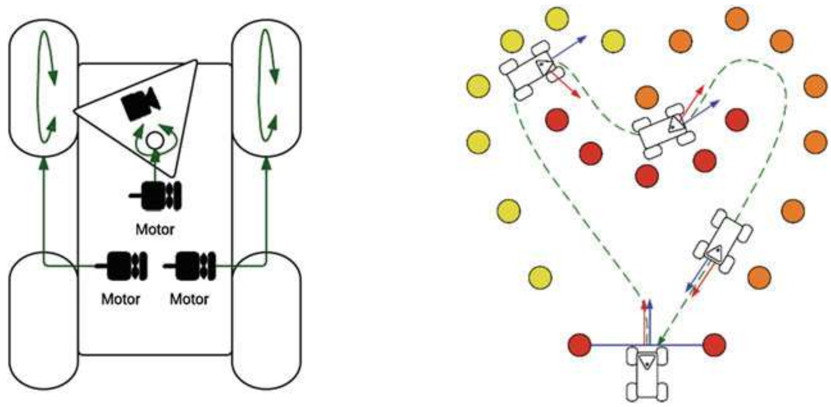

Fig. 2 Figure on the *left* represents a top view of a schematic drawing of the robot used in the experiment. Two motors control the rotation of the front-wheels and a third one drives the pan camera. The mobile vision is implemented to provide a better anticipation over the changes of trajectory. Figure on the *right* illustrates the behavior of the camera according to some examples of different kinds of bend. The *blue arrows* represent the instantaneous robot's direction and the *red arrows* indicate the orientation of the camera at the same instant. To notice that the angle between the two arrows is inversely proportional to the radius of curvature of the vehicle's trajectory

mechanism inspired from the human behavior [9, 10] was implemented by default, because it facilitates the teleoperation [1, 3]. Figure 2 (part right) shows examples of this visuo-locomotor coupling between camera and robot for different curves of the path.

2.2 Experimental Conditions

Manual Condition. In this condition the user has to manually control both the direction and the velocity of the robot. On the user interface control panel is represented concentric semicircles, which correspond to different levels of velocity (Fig. 3, on the left). Larger is the radius of the semicircle, higher is the velocity. So, the calculation of the robot's speed is based on the distance between one point on a semicircle and the center of the whole concentric semicircles. The robot's direction is inferred from the angle between the vertical of the remote control device and the fingertip of the user. The amplitude of the angles goes from 0° to 180°, rotating counterclockwise. If the user's fingertip is located between 0° and 90° the vehicle will turn right, with a curvature proportional to the angle between the vertical (90°) and the fingertip's pressure (more the finger's position tends to 0° more the robot turns right). On the other hand, if the fingertip's position is between 90° and 180° the robot will turn left (also, with an amplitude that depends on the angle from the vertical). The controller is constantly waiting for a command input from the touchscreen interface in order to update the velocity and direction of the vehicle.

Fig. 3 On the *left* side is a representation of the GUI for the Manual mode of driving. Each *concentric circle* represents a different speed (larger is the radius of the semicircle, higher is the velocity). On the *right* side is the user interface for the Biological condition. A single semicircle enables the user to directly control the direction of the robot and indirectly set the speed of the vehicle

Biological Condition. In this driving mode the user only controls the direction of the robot through the touchscreen interface. The velocity is automatic and depends on the trajectory of the robot. This velocity is calculated according to the instantaneous radius of curvature of the vehicle's trajectory, following the 2/3 Power Law. If the robot goes straight forward, it will move at a maximal speed of 30 cm/s. However, if its radius of curvature decreases (to the left or to the right), its velocity will reduce by a proportion of one-third. The GUI is represented by a single semicircle, because no manual settings of the speed are necessary (Fig. 3, on the right). This semicircle enables the user to control the direction of the vehicle. From the user's perspective, the way to guide the robot is identical to the Manual condition. The user has to use the right side of the semicircle to turn right and the left side to turn left. More the fingertip is located to the extremities of the semicircle (left or right) more the robot will turn sharply. The only difference between this mode and the Manual one is the fact that when the users pick a determined direction they also indirectly set a velocity to the robot, which will be proportional to the steering angle selected. If the Power Law is adapted to the remote control of an artefact, the matching between speed and steering angle should perfectly fit to the human's skills.

2.3 Experimental Protocol

Twenty people between 22 and 27 years old participated in the experiment. All of them had a normal or corrected-to-normal acuity. They were informed about the purpose of the experiment and they gave us their consent to participate. The experiment consisted in teleoperating a NXT mobile robot through an Android based mobile device. The participants were instructed to steer the vehicle as fast and safe (a minimum of collisions) as possible in an environment delimited by plastic blocks. The total distance of the path was approximately seven meters and was composed by several curves and changes in direction. As shown in Fig. 4, the course initiated with a straight line, then an approximatively 150° bend, then a 90° reverse curve, then again a 150° bend before a last straight line. A blue adhesive strip on the floor marked the start and finish line. The symmetric form of the

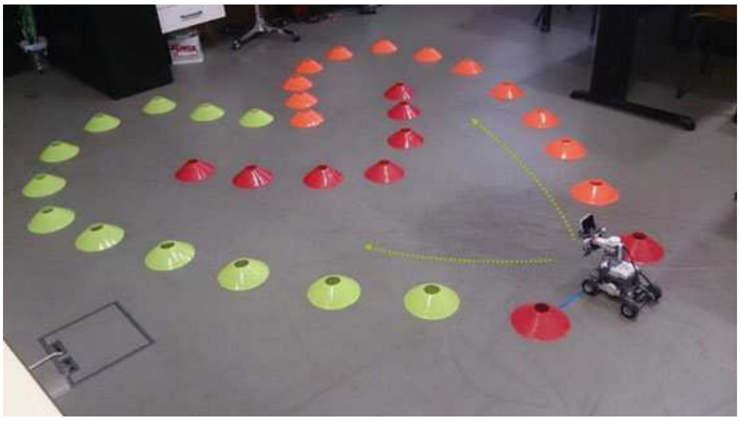

Fig. 4 Picture of the environment used in the experiment. The symmetric form of the path was chosen to easily alternate the course direction of the robot from one trial to the next: once clockwise and once counterclockwise (*green dotted lines*). This alternation was designed to minimize a machine-like way of driving the robot

environment was specifically designed to perform the path in both directions, clockwise and anticlockwise.

After a training session, each participant had to complete the path eight times: four times in the Manual condition and four times in the Biological condition. The order of the conditions were counterbalanced between the participants such as ten people started with the Manual driving and the ten others started with the Biological driving. This counterbalancing was designed to avoid a possible learning effect, which would bias the results of the experiment. For each of the main conditions (Manual vs. Biologic) the path was completed twice clockwise and twice anti-clockwise. Table 1 summarizes the experimental design used for this study. At the end of each trial the completion time and the number of collisions were recorded.

Table 1 Design of the experiment that shows the division of groups based on the order they execute each experimental condition (↻ for clockwise and ↺ for anticlockwise)

	Group 1	Group 2	Group 3	Group 4
List of participants	Participant 1 Participant 5 Participant 9 Participant 13 Participant 17	Participant 2 Participant 6 Participant 10 Participant 14 Participant 18	Participant 3 Participant 7 Participant 11 Participant 15 Participant 19	Participant 4 Participant 8 Participant 12 Participant 16 Participant 20
Sequence of the conditions	Manual ↺ Manual ↻ Manual ↺ Manual ↻ Biologic ↺ Biologic ↻ Biologic ↺ Biologic ↻	Manual ↻ Manual ↺ Manual ↻ Manual ↺ Biologic ↻ Biologic ↺ Biologic ↻ Biologic ↺	Biologic ↺ Biologic ↻ Biologic ↺ Biologic ↻ Manual ↺ Manual ↻ Manual ↺ Manual ↻	Biologic ↻ Biologic ↺ Biologic ↻ Biologic ↺ Manual ↻ Manual ↺ Manual ↻ Manual ↺

3 Results

The experimental data are statistically analyzed through ANOVA tests, for multi-variable, and T-tests, for the pairwise comparisons. The first analysis of the performance is about the completion time to execute the task. Results show a significant effect of the sessions on the completion time [F(3, 17) = 3.25; $p < 0.05$]. The pairwise analysis indicates a significant difference between session 1 and session 4 [$p < 0.03$]. These results show that the necessary time to steer the robot from the start line to the finish line decreases significantly from session 1 to session 4. No interaction effects are observed between the main conditions (Manual vs. Biological) and the sessions (1, 2, 3 and 4) [F(3, 17) = 1.68; N.S].

In addition, the overall comparison of the completion time between the Manual condition and the Biological condition shows a significant difference [F(1, 19) = 15.16; $p < 0.01$]. Figure 5 demonstrates that the mean completion time in the Biological condition is lower than in the Manual condition. The pairwise analyses confirm the significant difference in session 1 [F(19) = 3.19; $p < 0.01$], session 2 [F(19) = 2.11; $p < 0.05$] and session 3 [F(19) = 2.33; $p < 0.04$]. However, this statistical difference disappear in session 4 [F(19) = 1.40; N.S], although the Biological condition tends to remain faster than the Manual one. This last observation could be explained by the session effect that reduces the completion time in both, Biological and Manual conditions.

To complement the results, an evaluation of the occurrence of collisions was also carried out. The statistical analysis shows that the average number of collisions is significantly different over the sessions [F(3, 17) = 4.09; $p < 0.03$]. A pairwise analysis indicates a significant decrease of the collisions from session 1 to session 4

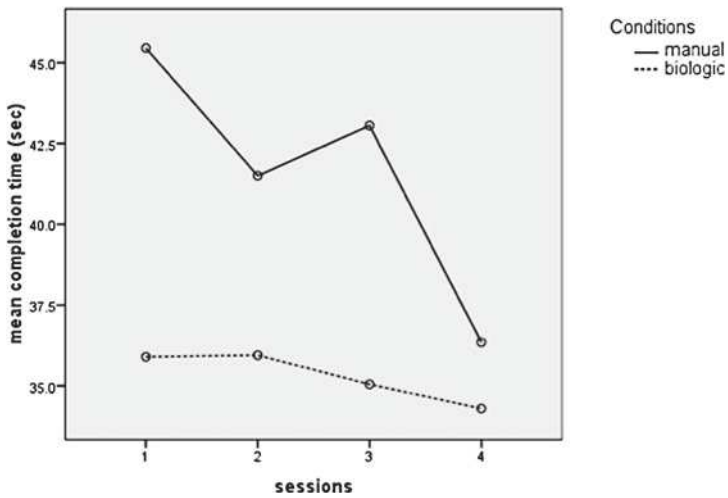

Fig. 5 Representation of the mean completion time (in seconds) for each of the main conditions (Manual vs. Biologic) against the four experimental sessions

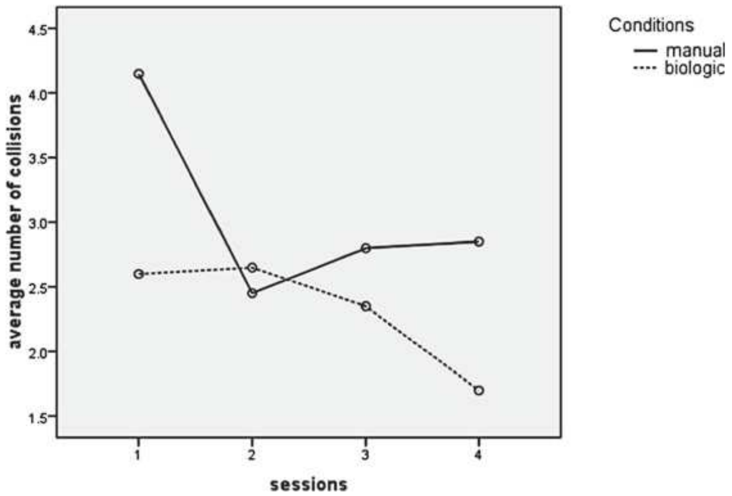

Fig. 6 Representation of the average number of collisions for each of the main conditions (Manual vs. Biologic) against the four experimental sessions

[$p < 0.02$]. These data point out that the participants' skill to drive the robot was improved over the experiment. There is no interaction effect between the two main conditions (Manual and Biological) and the four experimental sessions [$F(3, 17) = 2.08$; N.S].

The main comparison between the Manual vs. the Biological condition, over the whole sessions, indicates a significant difference [$F(1, 19) = 7.75$; $p < 0.02$]. As shown in Fig. 6, less collisions are produced in the Biological condition than in the Manual one. A statistical analysis session by session shows a significant difference in session 1 [$F(19) = 3.59$; $p < 0.01$] and session 4 [$F(19) = 2.50$; $p < 0.03$]. This last observation means that the learning effect do not enables the participants in the Manual condition to get driving skills as good as in the Biological situation.

4 Conclusions and Perspectives

This study consisted in analyzing the effect of the 2/3 Power Law on the control of a mobile robot. Two experimental conditions were compared. A first one in which the user had to manually control both, direction and velocity of the robot and a second one in which the robot's speed was automatically set according to the Power Law equation. The task of the participants was to remotely control the vehicle in order to complete the path as fast and safe as possible. The performance was recorded on four sessions. The statistical analyses shows that the completion time and the number of collisions significantly decrease across the sessions. This result can be explained by a learning effect of the participants, which leads to an improvement of the performance. The main comparison of the study shows that the velocity and precision to execute the task are significantly better in the Biological condition than in the Manual one. The advantage of the Biological mode can be explained by the fact that the automation of the velocity decreases the mental workload and sensorimotor resources of the teleoperators, who can focus their attention only on the way to guide the robot.

In a situation of human machine interaction, this is not always an advantage to automatize some parameters of the artefact. Usability rules that take into account the characteristics of the human being have to be followed. Here, the method proposed is to implement a human-like behavior to automatize the robot's velocity according to its trajectory. In the case of teleoperation, the anthropomorphic approach seems to be successful. Currently, a trend in the automobile industry is to create more autonomic cars [11]. However, the fact that drivers still want to keep the control is a big challenge for the constructors. As suggested by the results of this study, the use of human-like behaviors such as Power Law [12], Fitts' Law [13] … could be a promising process to automatize some key aspects of the vehicle's way of working. The potential success of such an approach is based on the fact that a vehicle that behaves as a human being would be easily understood and appropriated by the driver [14]. Future work will consist in testing the anthropomorphic approach in conditions more real than the laboratory and, also, in exploring other methods to implement human-like behaviors such as machine learning.

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