Using Psychophysiological Feedback to Enhance Physical Human Robot Interaction in a Cooperative Scenario

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Abstract—"Human state aware” systems, may be able to improve physical human-robot interaction (pHRI) by adapting their behavior and cooperation level accordingly to human psychophysiological feedback. This paper reviews the impact of the emotions on the motor control performance, and studies the possibility of improving the perceived skill/challenge relation on a multimodal neural rehabilitation scenario. For this purpose, a biocooperative controller that modulate the assistance given by a robotic haptic interface in reaction to undesirable physical and mental states was designed. Open and closed loop experiments made over eleven non impaired subjects, shows that psychophisiological feedback estimates, can help considerably on improving pHRI in a cooperative scenario.

I. INTRODUCTION

Emotions can have a big impact on motor performance, speed and variability [1]. Figure (1) shows a recent re-interpretation of the Yerkes and Dodson model where it is shown, how human performance change, in relation to the level of arousal experienced in a given situation depending on the difficulty of the task [2]. Mental states on the other hand, can be shaped by the perception of the subject performance on a moment given[3]. Figure (2) shows how mental states can change in relation to challenge and skill level perceived by a given subject. Those mental states can either increase or decrease performance accordingly. For instance, a boredom state, will tend to decrease performance, while a “flow” mental state will probably lead to better results on a given task.

This can be crucial in certain scenarios like in neural rehabilitation. Rigid spasticity (a motor disorder characterized by a velocity-dependent increase in tonic stretch reflexes[4] [5]) is a very common side effect suffered by post stroke patients. This collateral effect, gets worse in the presence of emotional stress or frustration [6].

There are many examples of modern upper limbs rehabilitation platforms [7] [8] [9]. Most of them includes rich multimodal interfaces enhanced with interactive virtual reality environments, high performance haptic robots, exoskeletons and more.

In spite of these remarkable efforts in offering a better overall experience, and so making therapies more fun and engaging, none of them takes into account any kind of possible and important psychosomatic disturbances and disengagement. Issues such as emotional and cognitive stress, excessive physical work demand, discomfort, pain, boringness and lack of motivation plays a key role on the human motor control performance levels (Figure 1).

Previous reported experiments [10] suggests that autonomic nervous system (ANS) activity distinguish among emotions. Moreover, the physiological expression of emotion is controlled by the neural circuitry of the brain. Emotional states are defined such that, for a specific state, there exists a probable set of somatic and ANS outputs (see Figure 3). There is a lot of research regarding psychophysiological signals measurements. An actual and very complete review can be found in [11].

For many years, psychophysiological measurements have been used to try to measure some responses of the ANS to external stimulus that affect people mood and engagement in a variety of interactive scenarios like human-human interaction[10], human computer interaction and virtual reality[12] [13] [14], and more to cite a few.

Previous work on Biocooperative closed loop control for rehabilitation evolved from including one signal (heart rate (HR)) feedback only [16], to more complex systems that includes Respiration rate (RR), Galvanic Skin Response (GSR), and Skin Temperature (SKT) feedback[17] [18]. Those systems were aimed to change the difficulty of the
controlling the perceived skill/challenge relation, by means of haptic cooperation, may lead to a better overall performance and satisfaction on a pHRI cooperative scenario, such as robotic aided neural rehabilitation therapies.

We present here an extension of our previous reported subject centered approach [16] method that includes the human into the loop by using novel bio cooperation techniques. This paper starts by describing a special virtual rehabilitation and haptic setups, designed to test the effects of the inclusion of a closed loop biocooperative controller. Then, a novel haptic strategy is proposed, in order to softly decouple the robot controller with the physiological compensator. Following, the auto tuning methods of the fuzzy logic compensator are also presented. Finally open and closed loops experiments and its results are reviewed and discussed.

II. METHODS

A. System setup

Our first hypothesis is that, “human state aware” robots, by means of biocooperative control, may be able to improve physical human-robot interaction pHRI by adapting their behavior and cooperation level accordingly to the human psychophysiological state. Our second hypothesis, is that
The robotic platform used for the experimental setup, is the PHYSIOBOT platform (Figure 4), which is presented in more detail, in [19]. Figure 5 Shows a block diagram, that describes the whole PHYSIOBOT platform architecture. In summary, an admittance controlled Staubli RX90 robot equipped with a JR3 force/torque sensor mounted at the end effector was used as the center hardware platform for the system. Several physiological signals are taken by ambulatory, easy to use sensors signal conditioned by a Biopac MP150 system. There is also a visualization platform that projects a simple interactive VR task oriented game, presented by a 32” and 17” LCD screens to the subject and the supervisor respectively. Finally, All the physiological and dynamic data is registered and stored as temporal series for online control and offline analysis.

B. VR game

![Virtual rehabilitation game](Figure 6)

The virtual scenario was designed as a virtual reaching neurorehabilitation task. It was created based on the simple and popular VR game (see Figure 6) reaching task oriented (catch the falling droplet). It was designed for it to be as less mental demanding and self explanatory as possible. Red droplets are spawn over a clean white background one at a time at a given velocity defined in pixels/sec. This, along with the haptic virtual scene properties, decides the difficulty of the task.

For experiments to be repeatable, droplets must not be created at random because that would result in changes in the total amount of work needed for the task to be successfully completed. To avoid this, droplets are created by reading a long predefined array of relative incremental positions starting for the center of the screen and increasing/decreasing with a variable step rate. This prevents people from memorizing positions and therefore avoids habituation issues, it also with a variable step rate. This prevents people from memorizing positions and therefore avoids habituation issues, it also helps on ensuring that the power needed to be transferred to the haptic interface trial by trial, is indeed homogeneous. It has a good distribution of points that helps the game to be difficult and varied enough for it to be very hard to catch falling droplets without the proper haptic assistance, thus making it perfectly suitable for the following studies.

1) Haptic setup: The haptic setup, consists on a virtual spring + damper like those seen on Figure (6) We will refer to their values from now on, as $K_{xx}$ and $B_{xx}$ respectively. As the equilibrium position of the spring is always re-positioned to be under the active droplet on the screen (the actual target) it enables us to play with a wide set of assistive forces in the task direction, proportional to the actual distance from its equilibrium point. The damper with a coefficient of $B_{xx}=150$ Ns/m, allows to continuously render a considerable viscous force field of on the task direction, which is parallel to patients coronal plane Figure(4). This velocity reactive term, makes reaching tasks highly physically demanding without the proper assistance.

2) Getting on time: In the virtual rehabilitation game presented before, the velocity of the falling droplets rises as the game difficulty does. From an energetic point of view, this lead to a rise in the total power needed to complete the reaching task.

A critically damped response will allow the system to get on the shortest time possible to the target, without any additional oscillations. With that in mind, we need to find a stiffness value $K_{max}$ for a certain well known value of damping and a settling time $T_s$ given by the timespan between 2 consecutive droplets.

In order to find $K_{max}$, we need to know some of the virtual and physical system constants involved. First of all, the apparent total mass $M_t$ as seen on Figure 6:

$$M_t = M_{arm}$$  \hspace{1cm} (1)

Apparent mass $M_{arm}$ is the mass seen by the robot end tip, and is obtained by measuring the resting force produced by the subjects arm weight. Note that the inertia from the robot is not relevant in this case, since admittance control tends to mask robot dynamics quiet well under low speed operating conditions.

Now from the natural frequency of a second order harmonic oscillator we know that:

$$K_{max} = \omega_n^2 + M_t$$  \hspace{1cm} (2)

So we need a value of $\omega_n$ that satisfies the settling time criteria for an overdamped system as follows:

$$t_s = \frac{6.6\xi - 1.6}{\omega_n}$$  \hspace{1cm} (3)

We also know from the damping relation that:

$$\xi = \frac{B}{2M_t\omega_n}$$  \hspace{1cm} (4)

Replacing 4 into 3 and solving for $\omega_n$ we have:

$$\omega_n = \frac{-3.2M_t + \sqrt{M_t^2 + 52.8t_sBM_t}}{4M_t}\frac{B}{\omega_n}$$  \hspace{1cm} (5)

Now is straight forward that from 2 we can obtain the value of $K_{max}$ that makes the system (without perturbations), able to marginally get on time. In order words, as long as the haptic interface renders the correct $K_{max}$, and in absence of subject resistance, the robot will be able to reach the droplets, with minimal power contribution, which in fact, is a desirable point.
Several physiological signals are collected online from the patient at therapy time. All the physiological measurements are performed via non invasive, ambulatory techniques. We are taking psychophysiological data from GSR, ECG and SKT, all of them are sampled at 100Hz as the authors didn’t find any high frequency components from none of the signals used.

1) HR: By using HR one can have an idea of the bodies changes in need for oxygen at a given time. Therefore, changes in heart rate can give us information of the physical effort made by the patient.

2) SKT: When the sympathetic nervous system is activated in response to stress, a reduction in peripheral circulation occurs. This peripheral vasconstriction leads to a reduction in skin temperature. The SKT is measured straight forward and does not require more than a baseline resting period to start measuring from it.

3) GSR: The galvanic skin response can be divided in two separate components. The skin conductance level (SCL) and skin conductance response (SCR). SCL is the slow varying baseline conductance value, while SCR is a fast varying response transient signal which rides over the SCL. The exact origin of the GSR’s are still controversial, nevertheless numerous studies and our own experience suggest that SCR’s are a good indicator of arousal and mental activity, while SCL reflects predominantly physical work load. The SCL measurement is straight forward, and does not require more than direct measuring from the GSR raw data to determine it. SCR on the other hand requires a more elaborated algorithm that includes a median smoothing filter, and a simple state machine that allows for robust SCR peak detection by using a morphological search of the SCR wave. It also allows to find the rise time and peak amplitudes which are important for analysis and statistics.

As SCR peaks are basically asynchronous events, it is important to transform that data to a continuous meaningful signal. To do this, we use the elapsed time between SCR peaks, that basically indicates how fast, those responses are being elected (more physical/mental activity regularly means faster responses).

D. Biocooperative control

The fuzzy logic controller was designed in order to respond to several possible input states coming from the gathered psychophysiological feedback. When dealing with rich multimodal environments including high performance haptic robots or another physical demanding interaction, psychological states estimates seems to be sometimes overshadowed by physiological responses on physically demanding tasks. Therefore trying to separate the effects of psychological from physiological situations is not an easy task. Instead we prefer to use psychophysiological measurements to get an idea of the overall psychophysiological states rather than separate them into physical load/state and psychological load/state. This reduces the logic to two possible conditions desirable and undesirable states.

Figure 8 shows a set of normalized signals corresponding to the previously defined states, and a normal(rest) state. A desirable state is that where the patient has low to medium levels of arousal, medium to high levels of emotional valence (pleasure) and also mid to high levels of dominance (sense of control of the situation). On the other hand, undesirable states could be either started by an over challenging situation that possibly lead to frustration with a significant decrease in dominance levels, or by an under challenging situation that leads to boredom and so a decrease in valence.

1) Tuning the FIS: Every FIS has two basic tunable set of parameters, the rules base, and the membership functions (MF) for each I/O. At this point of our research, we preferred to hard code the rules base based on different type of sources including Open loop observations with this same setup, bibliography, and previous experiments involving psychophsiology in pHRI scenarios from other groups [20].

On the other hand, MF were designed to be automatically calibrated after an open loop control task designed primarily for that task. The control task, consists on a 5 minutes virtual rehabilitation open loop task. This task consists of a VR game session with an adaptable skill game difficulty. The adaptation rule is very simple, every time the subject catch a droplet, the system penalizes you by softly augmenting the falling speed by 2 pixels/sec. On the other hand, if the subject misses a droplet, the system do the opposite and reduce the...
speed by the same amount. The idea with this, is to bring the subject to his maximum skill in which he will start to oscillate between winning and losing a lot. This is a stressful situation because the perceived skill level at some point, is normally inferior to the perceived challenge level (see Figure 11 to get a better idea).

E. The experiment

Eleven staff members from fundacion CARTIF, eight males and three females, between 28 and 48 years (mean age: 35 and std: 7.34) all of them with no clinical records of neural or motor deficiencies, participated in a simple experiment involving 2 virtual rehabilitation sessions of 5 minutes each, with an in-between pause of 5 minutes. The first task corresponds to the open loop control task explained before. The second task is similar to the first one, but instead, with the biocooperative loop turned on. At the end of the two sessions two self assessment questionnaires were presented to each subject. One was the popular Self Assessment Manikin test (SAM)[21], and the other was a plain 0-9 perceived Challenge/Skill ratio scale useful in comparing the two experiences.

Figure 11, shows the results of a control task. We can see, by looking at the red line, when exactly performance starts to decay. Notice that SCL, HR and SCR frequency levels, also rise at the very same time.

III. RESULTS

Fig. 11. Control task results for a single subject. From top to bottom, GSR(in micro Siemens), Game Score (points) and HR (in BPM), all of them on a 5 minutes timescale. Red vertical line, is a visual cue for the time when the subject starts to get aroused. Green horizontal line, is a cue for the "patients skill limit".

Fig. 12. Biocooperative task Results. Information and timescale are the same for Figure 11

1) Use the mean value to make all the inputs relative to it so it is always the center point of the "Medium" MF.
2) Use the std value as shown in Figure 9, to adapt the limits of the remaining MF.
3) Use the peak limits to adjust the min and max for the "Low" and "High" MF's values as also shown on that figure.

For the SCR, we can extract from the control task, the minimum time between SCR peaks. This parameter is highly dependent as there can be big differences on the SCR response speed caused by many factors like subjects being under psychopharmacotherapy treatment, or even under the effects of high caffeine levels. By using this information, one can adjust the SCR’s “high” MF from that starting point, and then adjust the following accordingly.

This way, the system is able to detect if the subject is entering his/her own "skill limits" and react, by augmenting the assistance output accordingly, and thus, the perceived skill level of that person.
A. Self reports and subjects mood

All reports from the self questionnaires revealed that all patients experienced a better skill/challenge relation in the Biocooperative task, compared to the control task. SAM tests reported also an increase in valence, dominance, and a little decrease in arousal, on the Biocooperative task.

B. Performance

We can see a clear increase in the score achieved on Figure 12 compared with the one in figure 11. As expected, because of the haptic assistance, the mean absolute force (MAF) done by the patient, decreased in a mean of 24.77% with a std:8.66%. However, on the other hand, the in game performance measured by the game score, improved in a mean of 275.38% with a std:79.35%.

C. Psychophysiological responses

Table I, presents the psychophysiological statistics for control and a biocooperative tasks. HR in (BPM), SCL in (micro Siemens) SKT in (Celcius over 33) and SCR’s is the SCR peak count for the 5 min timeline.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Control task</th>
<th>Biocooperative task</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR</td>
<td>m:3.82, std:8.71</td>
<td>m:8.46, std:6.46</td>
</tr>
<tr>
<td>SCL</td>
<td>m:3.63, std:0.73</td>
<td>m:6.05, std:0.47</td>
</tr>
<tr>
<td>SKT</td>
<td>m:3.25, std:0.24</td>
<td>m:3.65, std:0.04</td>
</tr>
<tr>
<td>SCR’s</td>
<td>72</td>
<td>45</td>
</tr>
</tbody>
</table>

TABLE I

PSYCHOPHYSIOLOGICAL STATISTICS FOR CONTROL AND BIOCOOPERATIVE TASKS

As expected, due to the biocooperative assistance, HR, SCL values and the number of SCR peaks dropped considerably from one task to another while SKT values on their side, didn’t not changed in a meaningful way.

IV. CONCLUSIONS AND FUTURE WORK

It seems that as a side effect of adapting the motor effort needed to complete the task with the help of Biocooperative control, leads to an increase in the perceived skill/challenge relation. Besides the performance boost, this could help on making therapies more engaging and thus helping lead to a better and more intense rehabilitation experience that can boost the neural plasticity process. Future work may be focused on improving the overall design of the FIS engine, by adding game difficulty corrections to see the effects of the two coupled modulations.

REFERENCES


