Vibrotactile haptic feedback for human-robot interaction in leader-follower tasks

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ABSTRACT

In this paper we explore a vibrotactile feedback paradigm which allows the human to intuitively interact in human-robot applications. In particular we focus on a haptic bracelet which helps the human to move along trajectories that are feasible for the leader-follower formation tasks. The bracelet consists of three vibrating motors circling the forearm and represents a non invasive way to provide essential information to the human. Experiments performed on a public of 15 subjects revealed the effectiveness of the proposed device.

Categories and Subject Descriptors

H.5.2 [**Information Interfaces and Presentation**]: User Interfaces—*haptic interfaces*

General Terms

Design, Human Factors, Theory

Keywords

Vibrotactile bracelet, Wearable haptic interfaces, Leader-follower formation, Human-robot interaction

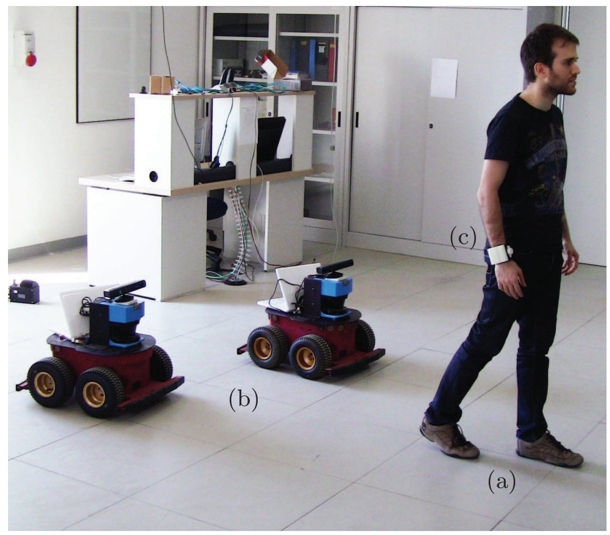

Figure 1: A human leader (a) is followed by a team of mobile robots (b) equipped with RGB-D cameras. A vibrotactile bracelet (c) allows the followers to inform the leader about the formation consistency.

1. INTRODUCTION

Robots can support humans in complex everyday tasks, such as indoor and outdoor navigation and information supplying, or carrying heavy objects. In the last decade, formation control has become one of the leading research areas in mobile robotics since multiple mobile robots can achieve a given task, faster, more robustly and more accurately than a single unit. In addition, a growing interest in human-robot interaction let recent studies [11,13] explore new strategies in mixed human-robot formation control. However these works as well as other recent researches, [3,8–10] provided only the possibility to exchange the information from the human to the robot, in terms of gesture recognition and human pose estimation and tracking.

Our idea is to introduce a duplex communication channel which allows the robot to send information to the human by using simple signals in terms of brain processing. Such approach may improve the cooperativity and interoperability.

A possible solution can be achieved via a *wearable haptic device* which provides suitable vibrotactile feedback. As with sound, a tactile stimulus is made up of a signal with varying frequency and amplitude, but, differently from the auditory feedback which needs a mental model in order to parse the information, tactile feedback directly engages our motor learning system [6]. Moreover, differently from cutaneous feedback, technologies for generating kinesthetic stimuli are typically cumbersome, have limited ranges of motion and although they can typically generate strong forces and realistically guide a human motion, they are typically designed only for some special applications [7]. Most of the research on cutaneous feedback has focused on providing stimuli on human finger pads, due to the high number of receptors located there. Recent works have started to explore other body parts for information display, mostly for

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navigation purposes and instruction of motor tasks.

In [2], the authors studied the possibility of presenting navigation information on a vibrotactile waist belt. Results indicated the usefulness of tactile feedback for navigation and, eventually, situational awareness in multitask environments. A similar device was proposed in [16], where an haptic belt was integrated with a directional sensor and a GPS system, and used as an intuitive navigation system.

In [6] the authors developed a robotic suit for improved human motor learning. The suit provides vibrotactile feedback proportional to the error between the effective and the learned motion. Strictly related are the works in [12, 15]. In [12] a set of user-worn bands that provide vibrotactile guidance for static pose was presented, while in [15] the authors presented the design of a wearable robotic teacher for forearm movements guidance. The system provides vibrotactile stimulations through a bracelet composed of four vibration motors disposed in quadrants. A vibrotactile orientation guidance device was also proposed in [4]. The authors mainly focused on the layout of the device as well as on the generation of different vibrating patterns. Finally, it is worth mentioning the vibrotactile device presented in [14] where the authors presented a deep study on the bracelet wearability, usability and capability of displaying vibrotactile stimuli. In this paper we focus on a vibrotactile bracelet which aims at improving the human-robot interaction in leader-follower formations where a human is followed by a group of nonholonomic mobile robots (see Fig. 1). The goal of the robot followers is to maintain a certain desired distance and orientation with respect to the human leader. Differently from the works presented above which mainly focused on navigation, in terms of driving the human towards a certain position or configuration, our purpose is to warn the human during his/her motion in order to let him/her move along trajectories that are feasible for the leader-follower formation tasks. Compared to [14], our bracelet represents a simplified version, although its essential design revealed good display performances in our leader-follower formation task.

The rest of the paper is organized as follows. Sect. 2 reviews some basic facts about the leader-follower formation control strategy presented in [1]. In Sect. 3, the haptic bracelet and the vibrotactile feedback are introduced. Finally, in Sect. 4, the main contributions of the paper are summarized and possible avenues for future research are discussed.

2. LEADER-FOLLOWER FORMATION CONSTRAINTS

In this section, we briefly recall the leader-follower formation control strategy proposed in [1], that we adapted to our mixed human-robot setup. For the sake of simplicity, we prefer to omit most of the mathematical calculi which led to the definition of leader-follower formation control law, focusing instead on the trajectory constraints which contribute to the generation of the vibrotactile stimuli.

Let us consider a nonholonomic robot $\mathbf{R} = (x, y, \theta)^T$ with initial condition $\overline{\mathbf{R}} \in \mathbb{R}^3$ and control $(v, \omega)^T$. Denote by $\mathbf{P}(t) = (x(t), y(t))^T$ the position of $\mathbf{R}$ at time t, $\theta(t)$ its heading, $\boldsymbol{\tau}(\theta(t))$ the normalized velocity vector and $\boldsymbol{\nu}(\theta(t))$ the normalized vector orthogonal to $\boldsymbol{\tau}(\theta(t))$. If we assume $v(t) > 0$ then the (scalar) curvature of the path followed by the robot at time t is $\kappa(t) = \omega(t)/v(t)$.

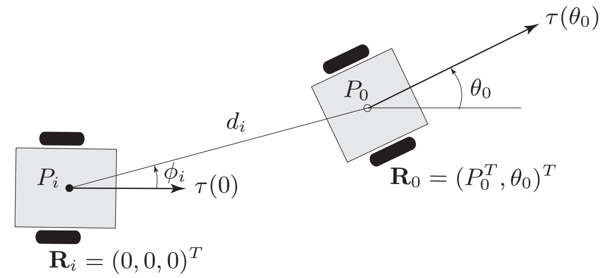

Figure 2: The leader $\mathbf{R}_0$ and follower $\mathbf{R}_i$ are in (d_i, ϕ_i)-formation. Differently from [1], the pose of the leader is here expressed in the follower's reference frame.

We suppose that every robot $\mathbf{R}$ which takes part to the team satisfies the trajectory constraint $(V_p, K_p^-, K_p^+) \in \mathbb{R}^3$, $\forall\, t \geq 0$

$$0 < v(t) \leq V_p, \tag{1}$$

$$K_p^- \leq \kappa(t) \leq K_p^+ \,. \tag{2}$$

This constraint is assumed to be the mechanical limitation common to all the robots considered in this paper. Let us now turn our attention to the formation formulation and suppose $\mathbf{R}_0$ be the formation leader and $\mathbf{R}_i$, $i = 1 \dots N$ be the followers. $\mathbf{R}_0$ and $\mathbf{R}_i$ are in (d_i, ϕ_i)-formation with leader $\mathbf{R}_0$ at time t, if

$$\mathbf{E}(t) = \mathbf{P}_0(t) - d_i\, \boldsymbol{\tau}(\phi_i) = 0 \tag{3}$$

Suppose now that the robots $\mathbf{R}_0$, $\mathbf{R}_i$ are initially not in formation, i.e. (3) is not verified at $t = 0$. If the following properties hold:

$$0 < W_0 \leq v_0(t) \tag{4}$$

$$\begin{array}{rcccccl} -\frac{1}{d_i} & < K_0^- & \leq K_0^+ & < \frac{1}{d_i \cos\phi_i} & , & \text{if} & \phi_i \geq 0 \\ -\frac{1}{d_i \cos\phi_i} & < K_0^- & \leq K_0^+ & < \frac{1}{d_i} & , & \text{if} & \phi_i < 0 \end{array} \tag{5}$$

$$\widetilde{K}_0^- < K_0^- \leq K_0^+ < \widetilde{K}_0^+ \tag{6}$$

$$\begin{aligned} V_0 \cos \big(& min(0, (\arcsin(K_0^+ d_i \cos\phi_i) - \phi_i)\,, \\ & (\phi_i - \arcsin(K_0^- d_i \cos\phi_i))) \big) < V_p \cos\phi_i \end{aligned} \tag{7}$$

where

$$\widetilde{K}_0^\pm = (\text{sign } K_p^\pm)\big(((K_p^\pm)^{-1} - d_i \sin\phi_i)^2 + d_i^2 \cos^2\phi_i\big)^{-\frac{1}{2}}\,, \tag{8}$$

then there exists $\bar{\epsilon} > 0$ such that for any $\epsilon : 0 < \epsilon < \bar{\epsilon}$, for any robot $\mathbf{R}_i$ with initial condition $\overline{\mathbf{R}}_i$, there exist suitable controls v_i, ω_i, such that $\mathbf{R}_0$ and $\mathbf{R}_i$ are asymptotically in (d_i, ϕ_i)-formation.

Eq. (4)-(7) represent the velocity and curvature constraints that the formation leader should satisfy at all the time. When the leader is a mobile robot, it is relatively simple to force the robot to satisfy such constraints. On the contrary, in presence of a human leader, it is necessary to establish a simple communication channel between the human and the robot such that the leader is warned when he/she is violating a possible constraint.

In the next section we present the vibrotactile bracelet used to allow the robots to communicate with the human.

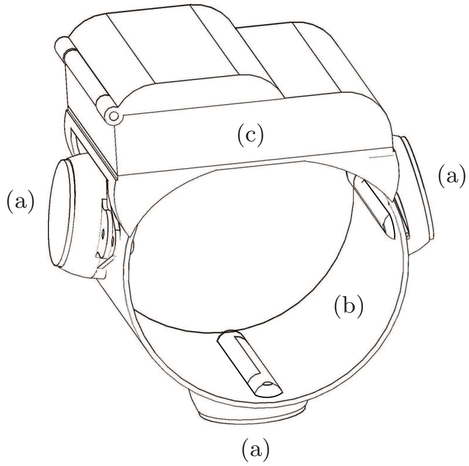

Figure 3: The human-robot interaction is achieved via a vibrotactile bracelet equipped with three vibrating motors (a): L (left), C (center) and R (right) attached to an elastic strap (b). The three motors are disposed equidistantly in order to improve the vibrotactile perception. A 9V battery and an Arduino board are disposed on the back of the forearm (c).

3. VIBROTACTILE BRACELET

Recent studies have demonstrated that a bracelet shape with three vibrating motors circling the forearm ensures a sufficient distance between the vibro-motors while at the same time covers a minimum forearm area [4].
Following this layout, we designed a wearable actuated device in which three vibro-motors, L (left), C (center) and R (right) are independently controlled via an external PC using the bluetooth 802.11 communication protocol, (see Fig. 3). The communication is realized with a RN41 bluetooth module connected to an Arduino Nano board. The bracelet is equipped with three LilyPad Vibe Boards with 10mm Shaftless Vibration Motors. An Atmega 328 microcontroller installed on the Arduino Nano board is used to independently control the vibration amplitude of each motors. The microcontroller controls the external actuators using 3 PWM outputs, each one fixed at 5V, 800Hz. The haptic bracelet is powered by a 9V, 200mAh battery. The minimum duty-cycle required to start the motor rotation is 0.2 and the amplitude of the vibration and its frequency increase proportionally in the duty-cicle. The maximum vibration frequency of each motor is 200Hz while the maximum amplitude of vibration is 0.8G.

3.1 Generation of the vibrotactile feedback

Let f_M, f_m be the maximum and minimum vibration frequency of each motor and $f_i(t)$ the vibration frequency of motor $i \in \{L, C, R\}$ at time t. As discussed in Sect. 2, the leader constraints can be divided in velocity and curvature constraints. The curvature constraints involve the activation of the lateral motors while the velocity constraints will be displayed through the central motor of the bracelet. Our vibrotactile feedback briefly consists in activating the vibro-motors as soon as the leader approaches the formation constraints within a given threshold, and increasing the vibration frequency proportionally to the constraints violation.

The curvature of the path followed by the leader at time t is $\kappa_0(t) = \omega_0(t)/v_0(t)$ with $v_0(t) > 0$. Substituting (2) in (5) and introducing the curvature threshold value $\alpha_c \in \mathbb{R}^+$, we obtain the following curvature constraints,

$$\begin{array}{ll} -\frac{1}{d} < -\frac{1}{d} + \alpha_c \leq \kappa_0(t) \leq \frac{1}{d\cos\phi} - \alpha_c < \frac{1}{d\cos\phi} & \text{if } \phi \geq 0 \\ -\frac{1}{d\cos\phi} < -\frac{1}{d\cos\phi} + \alpha_c \leq \kappa_0(t) \leq \frac{1}{d} - \alpha_c < \frac{1}{d} & \text{if } \phi < 0. \end{array} \quad (9)$$

Let $\delta^+(t)$, $\delta^-(t)$ the amount of violation of the given constraints at time t, when $\omega_0(t)$ is positive and negative. From (9) we obtain,

$$\delta^+(t) = \begin{cases} \kappa_0(t) - \frac{1}{d\cos\phi} + \alpha_c & \text{if } \phi \geq 0 \\ \kappa_0(t) - \frac{1}{d} + \alpha_c & \text{if } \phi < 0. \end{cases}$$

$$\delta^-(t) = \begin{cases} -\frac{1}{d} + \alpha_c - \kappa_0(t) & \text{if } \phi \geq 0 \\ -\frac{1}{d\cos\phi} + \alpha_c - \kappa_0(t) & \text{if } \phi < 0 \end{cases}$$

If $max(\delta^+(t), \delta^-(t)) \geq 0$, the human is approaching the curvature constraints, consequently, the following vibrational feedback is sent to the motors,

$$f_i(t) = (f_M - f_m)\frac{max(\delta^+(t), \delta^-(t))}{\alpha_c} + f_m \quad (10)$$

with

$$i = \begin{cases} L & \text{if } \delta^+(t) \geq 0 \\ R & \text{if } \delta^-(t) \geq 0. \end{cases}$$

Regarding the human linear velocity $v_0(t)$, from (1), (4) and considering a velocity threshold value $\alpha_l \in \mathbb{R}^+$, we obtain that $v_0(t)$ should fulfill the following constraint,

$$0 < W_0 < W_0 + \alpha_l < v_0(t) < V_0 - \alpha_l < V_0, \quad (11)$$

with V_0 satisfying eq. (7). If the leader is moving too fast, i.e. $v_0(t) \geq V_0 - \alpha_l$, the amount of constraint violation is,

$$\delta^+ = v_0(t) - V_0 + \alpha_l$$

and a vibration with the following frequency is generated by the central motor in the bracelet,

$$f_C(t) = (f_M - f_m)\frac{\delta^+(t)}{\alpha_l} + f_m. \quad (12)$$

In addition, the constraint in (11) sets a lower bound on the linear velocity $v_0(t)$. Although W_0 can be arbitrarily small, this bound may be violated every time the leader decides to stop, for example the leader starts to slow down and $v_0(t) \leq W_0 + \alpha_l$. In this case, we need to send to the central motor a signal different from (12) in order to be correctly perceived by the human. We arbitrarily decide to use a pulse wave with a maximum frequency equal to $(f_M + f_m)/2$, a period of 0.2s and a duty-cycle of 0.5.

3.2 Evaluation of the haptic bracelet

In this section we evaluated the bracelet behavior performing vibrotactile signals comparable with the one presented in Sect. 3.1.
The proposed device has been tested on 15 healthy male subjects (aged 23 to 33, all right-handed). Although tactile

stimulations under 100Hz improve the spatial resolution of the vibrations' perception [5], we preferred to use a vibration frequency between 80Hz and 200Hz, which turned out to be more comfortable for the subjects.

We performed two different experiments. In the first one a single signal or a combination of signals at different vibrational frequencies was sent to the haptic bracelet, this experiment allowed us to understand if the human is capable to recognize which motor is vibrating. In the second experiment two consecutive signals with different frequencies were sent to the same motors. This experiment showed the minimum frequency variation the user can perceive. Each subject has been initially trained with a training set of 20 trials. For both the experiments, the evaluation set was composed of two sets of 30 trials each. We avoided cases in which all motors were turned on and cases in which the left and right motors were contemporary activated, since they cannot be encountered in real applications.

In the first experiment, the users could correctly perceive and distinguish the 83% of the vibrotactile stimuli. In particular, a single signal was always correctly perceived. The average time elapsed to perceive the vibration was 1.1267s with standard deviation of 0.4329s. An in-depth analysis revealed that in the presence of two signals, the subjects could always correctly perceive at least one of the two involved stimuli, usually the most intense. This means that in real world experiments, the leader should always be able to perceive the vibrotactile feedback relative to the constraint that is violated the most.

In the second experiment, the users could correctly perceive the 85.61% of the frequency variation of at least 30Hz. This means that the user can perceive, within a good percentage, if the constraint violation is increasing or decreasing.

4. CONCLUSIONS

In this paper we presented a preliminary setup where a vibrotactile bracelet allows the human-robot interaction in leader-follower formation tasks. The bracelet showed the ability to exert vibrotactile signals which can be correctly perceived by the human user. In this regard it can be effectively used in the leader-follower formation control proposed in [1]. On going research aim at testing such device in the proposed scenario as well as extend its applicability to other case studies.

5. ACKNOWLEDGMENTS

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