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Withdrawal Strategy for Human Safety based on a Virtual Force Model

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***Abstract*— The Human-Robot Interaction gets increasingly closer. In consequence, human safety has become a key issue for the success of the symbiosis between humans and robots. When the minimum distance between a human and a robot is too short, it can be naturally considered that the probability of a collision increases. Therefore, we consider that the robot should increase the distance to the human when the human is getting closer. We propose Withdrawal strategy as a method that aims to increase the distance by moving the end-effector not only away from the human but also to a parking position that can be previously assessed to be safer. To withdraw the end-effector, we use a virtual force model consisting of two virtual forces: a repelling force exerted by the human and an attractive force exerted by the parking position. We carry out experiments using a human-sized humanoid robot and five human subjects, and report the task completion time to evaluate the efficiency of the robot when performing a simple task.**

I. INTRODUCTION

The economical benefits of the symbiosis between humans and robots have produced an increasing necessity of deploying them side by side in a shared workspace [1]. This ever closer Human-Robot Interaction (HRI) involves safety issues and requires new methodologies to ensure human safety when the robot is operating near humans.

We have already proposed Asymmetric Velocity Moderation (AVM) [2] as a reactive strategy for human safety. Using AVM, the robot can asymmetrically restrict its speed, in order to avoid harming a human that happens to be in its workspace. This may lead to a situation where the minimum distance between the human and the robot is too short, e.g., the robot comes to a complete stop but the human continues to approach. When human and robot are too close, an increase in the minimum distance can naturally imply a decrease in the probability of a collision. This suggests that, under those circumstances, making the robot increase the distance from the human can benefit human safety.

In this paper, we propose Withdrawal strategy whose purpose is to increase the distance between human and robot when the current minimum distance is too short. Withdrawal strategy makes the robot move the end-effector away from the human when the human is getting closer.

In some measure, Withdrawal resembles the human movement of withdrawing an arm when another person is trying to reach the same region of a shared workspace, e.g., when two people try to reach the same object at the same time and get too close, one of them may withdraw his arm. Therefore,

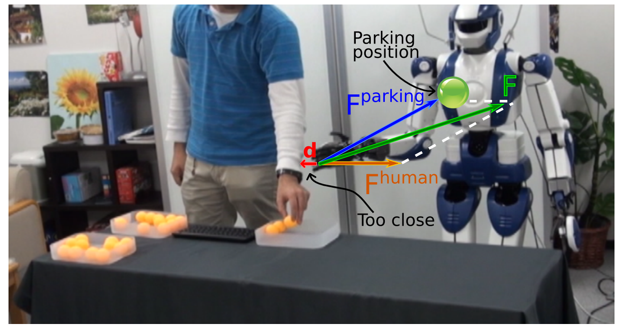

Fig. 1. Virtual force $\mathbf{F}$ obtained from a repelling force $\mathbf{F}^{\text{human}}$ exerted by the human and an attractive force $\mathbf{F}^{\text{parking}}$ exerted by a parking position (represented by a sphere).

Withdrawal strategy can be used for situations where human and robot are trying to reach a location in the same region and the distance between them becomes too short.

Withdrawal strategy temporarily modifies the end-effector trajectory in order to make the robot increase the distance from human when the current minimum distance is below a determined threshold. After increasing the distance, Withdrawal strategy moves the end-effector back to the location where the strategy was engaged, which allows the robot to continue its task. To withdraw the end-effector, we use a virtual force model consisting of two virtual forces: a repelling force exerted by the human and an attractive force exerted by a parking position, as shown in Fig. 1.

Moreover, Withdrawal strategy uses AVM as a low-level component for human safety, i.e., the target velocity proposed by Withdrawal strategy is restricted by AVM. We use AVM since it keeps the robot's efficiency to complete its task while ensuring human safety is preserved at all times.

The experiment results validate the use of Withdrawal as an strategy to increase the distance between human and robot while preserving the robot's efficiency, as much as possible.

As a result of previous research [3], the authors proposed the use of a virtual force that pushes the robot away from the human. Such virtual force considers the minimum distance, the relative velocity and the effective inertia. Nevertheless, since the end-effector is only moving away from the human, the resulting configuration of the robot and its end-effector location may be unpredictable. In our proposed Withdrawal strategy, we consider safer to make the motion of the end-effector converge to a known location where the robot can park the end-effector. Also in the previous method [3], applying the virtual force that causes the end-effector to move away from the human leads to the abandonment of the task. As stated in [4], this method is not easily reproducible

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due to its dependence on other components. Our proposed Withdrawal strategy makes the end-effector go back to the configuration where the strategy was engaged, allowing the robot to resume its task.

A human-aware manipulation planner is proposed in [5], where the authors consider safety, visibility and comfortability as cost functions to take into account by the planner. Nevertheless, safety is assessed considering only the distance to the human. In our approach, we consider not only distance but also the direction of the motion.

Lacevic and Rocco [4] proposed the kinetostatic danger field (KSDF) which also considers the direction of the motion. The authors exploit the kinematic redundancy to obtain safer postures and stop the end-effector to preserve task completeness. When the KSDF passes certain threshold, the end-effector is forced to leave the target position to which it goes back when the danger has decreased. Nevertheless, the end-effector motion is driven by the KSDF only away from the obstacle which may lead to an unpredictable position of the end-effector. Our proposed method aims to make the end-effector move not only away from the human but also towards a known safer location.

In this paper, Section II presents a brief overview of AVM, Section III details the proposed Withdrawal strategy, Section IV describes the experimental setup and the experiments carried out, and Section VI concludes this paper.

II. ASYMMETRIC VELOCITY MODERATION

AVM [2] is a reactive strategy for human safety that restricts the velocity of the end-effector according to the distance between human and robot. Similarly to [4] and [6], AVM considers also the direction of the motion. Since AVM also aims to maintain the robot's efficiency, AVM preserves the velocity of the input trajectory as much as possible, unless such velocity compromises human safety.

More specifically, AVM restriction is based on the minimum distance, and the angle between the displacement vector (i.e., vector formed by the closest points between human and robot) and the velocity vector. Even though the original algorithm was developed considering only the end-effector velocity, the core concept can be extended to all joints or points on the robot.

The reason to consider the direction is that even though the velocity directed towards the human should be firmly restricted, it is possible to relax the restriction of the velocity directed away from the human, even if the distance is short. Thus, the limitation of the end-effector velocity is defined asymmetrically for each direction.

Similarly to the KSDF proposed in [4], more than just providing a mere restriction for *away* and *towards*, AVM provides a specific restriction for all directions. To calculate such restriction, AVM uses an auxiliary circle (with no physical interpretation) as shown in Fig. 2. In such circle, one is the human side and the other is the robot side. r is radius of the circle, r' is an auxiliary length, θ is the angle between the displacement vector and the end-effector velocity vector, and $f_{\text{aux}} \in [0, 1]$ is the restriction that AVM outputs. By linearly changing r and r' according to distance (i.e., shrinking and expanding the circle and moving the point where r' finishes), we can calculate the restriction f_{aux} using Law of Cosines.

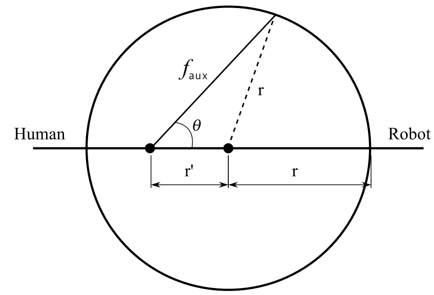

Fig. 2. Auxiliary circle used to calculate f_{aux}.

In the human safety system that has been designed, AVM is in charge of guaranteeing human safety as a low-level component, while other strategies provide specific behaviors for the robot, e.g., Withdrawal strategy which makes the robot increase the distance to the human. Thus, AVM will audit and restrict the speed of the robot derived from other strategies in order to achieve a safe HRI.

III. WITHDRAWAL STRATEGY

In this section, we propose Withdrawal strategy whose purpose is to increase the distance between the human and robot when the current distance is too short. This is because such distance increase can naturally imply a decrease in the probability of a collision. We use a virtual force model to modify the end-effector velocity and move it not only away from the human but also towards a parking position, which can be previously asserted as a safer location. Moreover, after moving the end-effector, we make the end-effector go back to the previous location in order to allow the robot to continue its task.

A. Overview

In order to modify the trajectory of the end-effector to increase the distance, Withdrawal makes use of a force model consisting of two virtual forces: a repelling force exerted by the human, and an attractive force exerted by a parking position, as shown in Fig. 3. Therefore, by using these forces, Withdrawal modifies the velocity of the end-effector making the robot to move not only away from the human but also to a parking position, which is assumed to be a safer location, e.g., near the robot's chest.

We can define *TakeOut* as the motion of placing the end-effector in a safer location and it conforms the first phase of Withdrawal strategy. *TakeOut* starts when the distance to the human is too short and the restriction calculated by AVM is very high, i.e., the speed of the end-effector is almost zero. Once the end-effector has been withdrawn enough to increase the distance, the *PlaceBack* phase starts. *PlaceBack* is in charge of moving the end-effector from the location achieved by *TakeOut* to the location where Withdrawal strategy was engaged, in order to allow the robot to resume the task. In

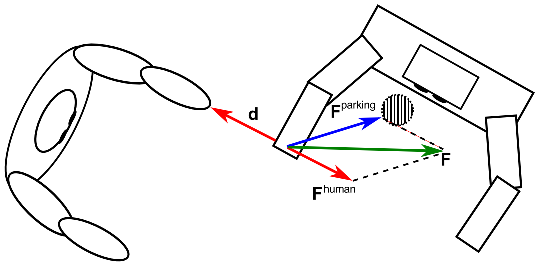

Fig. 3. Schematics of the virtual force $\mathbf{F}$, resulting of the contributions of $\mathbf{F}^{\text{human}}$ and $\mathbf{F}^{\text{parking}}$. The circle indicates the parking position.

summary, Withdrawal pauses the task by creating a temporal deviation from the original trajectory, increases the distance from human, and then goes back to where it started to allow the robot to continue with the task.

Furthermore, since the motion produced by Withdrawal to displace the end-effector is audited by AVM, the resulting trajectory can be considered as a safe trajectory.

B. Virtual Force Model of Withdrawal

In order to modify the velocity of the end-effector, we can introduce two virtual forces: a repelling force $\mathbf{F}^{\text{human}}$ exerted by the human, and an attractive force $\mathbf{F}^{\text{parking}}$ exerted by a parking position, as shown in Fig.3.

These forces are inspired in the Social Force Model introduced in [7]. As explained in [8], the Social Force Model can describe the interactions between pedestrians by making use of social forces. Such forces aim to model the behavior of the human motion, which is considered to be affected by the motion of other humans and the environment. Therefore, these forces may be derived from the motivation of the human to reach his goal, the repulsive effect of obstacles, physical constraints, and so on.

Luber *et al.* [8] define the social forces as follows:

$$\mathbf{f}_{i,k}^{\text{soc}} = a_k \exp\left(\frac{r_{i,k} - d_{i,k}}{b_k}\right)\boldsymbol{n}_{i,k} \tag{1}$$

where i is the index of the human receiving the influence of the force, k is another human or an object, a_k represents the magnitude of the force, and b_k denotes the range of the force. Since humans and objects are represented as circles, r_i and r_k are the radius of the human i and the radius of the human or object k that is exerting the force. $r_{i,k}$ is the sum of these radii and $d_{i,k}$ is the distance between the centers of the circles. Finally, $\boldsymbol{n}_{i,k}$ is a normalized vector that points from the human or object k to the human i.

Moreover, Luber *et al.* [8] add an anisotropic factor to constrain the influence of the force exerted by the human or object k depending on its location with respect to the human i. By doing this, the humans or objects in front of the human i will have more influence than the humans or objects that are behind.

Even though the Social Force Model was originally developed to address the interaction between pedestrians, it can be modified to be applicable to other cases not only involving human-human interaction but also HRI. This is due to the fact that the core concept of the Social Force Model is to use virtual forces to model the behavior of human motion and its relations with the environment, whether if such environment is populated by other humans or robots.

In the literature it is possible to find modifications to the Social Force Model to overcome counterintuitive results when applied to the motion of an isolated pedestrian as in [9], or to adapt the Social Force Model to allow the robot to navigate in a more natural way as in [10].

We can modify the Social Force Model in such way that the contributions of the forces exerted by the human and by the parking position are summarized in a resulting force $\mathbf{F}$, which will be used to modify the end-effector velocity in order to move the robot to a safer location.

The force $\mathbf{F}^{\text{human}}$ is a repelling force derived from the human proximity which causes the end-effector to move away from the human. This force decreases proportionally to the distance to its source, i.e., proportionally to the minimum distance between human and robot, and is modeled as:

$$\mathbf{F}^{\text{human}} = M\exp\left(\frac{-d}{R}\right)\boldsymbol{n} \tag{2}$$

where M represents the magnitude of the force and R its range, and d is the minimum distance between human and robot. The vector $\boldsymbol{n}$ is a normalized vector that describes the direction of the force. Such vector $\boldsymbol{n}$ is obtained by normalizing the displacement vector but using its opposite direction, i.e., from the human to the robot.

The absence of an anisotropic factor [8] in the Equation 2 is because we pretend to include the effect of the human proximity from all directions, since eventually AVM will restrict the speed of the robot according to the HRI constraints.

Furthermore, the force $\mathbf{F}^{\text{parking}}$ is an attractive force that makes the end-effector move to a fixed position. We assume that it is safe to park the end-effector in such position. This assumption is sustained on a simple assertion of the characteristics presented by the robot when its end-effector is in such location, e.g., the potential energy of the robot's arm, the effect of the configuration on the robot's balance, the lack or decrease of reachability by the human, and so on. Therefore, the parking force $\mathbf{F}^{\text{parking}}$ is modeled as follows:

$$\mathbf{F}^{\text{parking}} = A\mathbf{p} \tag{3}$$

where A is the magnitude of the force, and $\mathbf{p}$ is the normalized vector pointing from the current location of the end-effector to the parking position. We set $\mathbf{F}^{\text{parking}}$ as a constant force in order to make the end-effector converge to the parking position.

We can obtain a force $\mathbf{F}$ by adding the contributions of both forces, $\mathbf{F}^{\text{human}}$ and $\mathbf{F}^{\text{parking}}$. Using $\mathbf{F}$ it is possible to move the end-effector not only away from the human but also to a parking position. Finally, the motion of the end-effector will be calculated as $\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{V} = \frac{\mathbf{F}}{m}$, where m is the human mass and $\mathbf{V}$ is the resulting velocity. We use the human mass for two reasons: first, human mass is clearly the mass involved in the force exerted by the human; and second, the parking position is massless and assigning it a mass would imply further considerations about the effect on the resulting velocity.

For a very small fraction of time Δt, we can obtain the variation in the velocity $\Delta \mathbf{V} = \frac{\mathbf{F}}{m}\Delta t$. This variation will be added to the current velocity of the end-effector in order to modify its motion, i.e., $\mathbf{V}' = \mathbf{V}_{\text{curr}} + \Delta \mathbf{V}$. Since the velocity of the end-effector is almost zero when the Withdrawal strategy is engaged, $\mathbf{V}_{\text{curr}}$ can be neglected. Therefore, $\Delta \mathbf{V}$ represents the velocity vector that will be used as the end-effector velocity vector to withdraw the robot's arm.

C. Phases of Withdrawal

The execution of Withdrawal strategy can be divided in two phases: *TakeOut* and *PlaceBack*. *TakeOut* alludes to the behavior of the robot starting from the engagement of the strategy until it stops in a safer location. *PlaceBack* refers to the robot's behavior from the safer location to the end-effector location where the strategy was engaged so that the robot can resume its task. We assume that if the task can be paused and a temporal deviation from the original trajectory does not impede the robot to resume the task, Withdrawal will not affect the success of the task.

As Withdrawal is restricted by AVM, Withdrawal inherits the properties of AVM, e.g., being suitable for tasks that do not depend on a specific end-effector velocity. Meanwhile, Withdrawal is suitable for tasks that are not sensitive to a temporal abandonment and that are resumable, e.g., picking up objects, drawing, turning a crank, and so on.

The Withdrawal algorithm is as follows:

TakeOut:

1.a. Calculate a force $\mathbf{F}$ using the forces $\mathbf{F}^{\text{human}}$ and $\mathbf{F}^{\text{parking}}$.

1.b. Determine the variation on the velocity $\Delta \mathbf{V}$ from the force $\mathbf{F}$.

1.c. Obtain $\mathbf{V}'$ by adding $\Delta \mathbf{V}$ to the current end-effector velocity $\mathbf{V}_{\text{curr}}$.

1.d. Calculate the target joint angles $\mathbf{q}(t + \Delta t)$ that satisfy $\mathbf{V}'$.

1.e. Use $\mathbf{V}'$ to modify the end-effector velocity.

1.f. Output the target joint angles $\mathbf{q}(t + s\Delta t)$, where s is the trajectory scaler imposed by AVM.

1.g. Stop modifying the end-effector velocity and start *PlaceBack*, when one of the following happens:

- i) The minimum distance $||\mathbf{d}||$ is greater than a threshold D_{diseng}.
- ii) The displacement of the end-effector is greater than a threshold $D_{withdrawing}$.
- iii) The end-effector reaches the parking position.

PlaceBack:

2.a. Calculate the target joint angles $\mathbf{q}(t)$ from the trajectory defined by a cubic polynomial to move the end-effector back to the location where *TakeOut* started.

2.b. Output the target joint angles $\mathbf{q}(\tilde{t} + s\Delta t)$, where s is the trajectory scaler imposed by AVM.

2.c. Update the internal time $\tilde{t} \leftarrow \tilde{t} + s\Delta t$

2.d. If the target location is reached, disengage Withdrawal strategy to allow the robot to continue its task.

Algorithm 1 *TakeOut*

Input: Δt, $\mathbf{q}_{\text{curr}}$, $\mathbf{d}$

Output: $\mathbf{q}^*$

0) Save current configuration for *PlaceBack*:
   $\mathbf{q}_{\text{eng}} \leftarrow \mathbf{q}_{\text{curr}}$
1) $\mathbf{F} \leftarrow \mathbf{F}^{\text{human}} + \mathbf{F}^{\text{parking}}$
2) Obtain $\Delta \mathbf{V}$ from $\mathbf{F}$:
   $\Delta \mathbf{V} \leftarrow \frac{\mathbf{F}}{m}$
3) Calculate the new velocity of the end-effector:
   $\mathbf{V}' = \mathbf{V} + \Delta \mathbf{V}$
4) Calculate $\dot{\mathbf{q}}'$ for $\mathbf{V}'$:
   $\dot{\mathbf{q}}' \leftarrow \mathbf{J}^{\sharp}(\mathbf{q}_{\text{curr}})\mathbf{V}'$
5) Obtain the target joint angles:
   $\mathbf{q}(t + \Delta t) \leftarrow \dot{\mathbf{q}}'\Delta t + \mathbf{q}(t)$
6) AVM restricts the target joint angles:
   $\mathbf{q}^* \leftarrow \mathbf{q}(t + s\Delta t)$
7) Finish *TakeOut* and, thus, disengage Withdrawal if:
   a) $||\mathbf{d}|| > D_{diseng}$, or
   b) end-effector displacement $> D_{withdrawing}$, or
   c) end-effector arrives to the parking position

Algorithm 2 *PlaceBack*

Input: Δt, $\mathbf{q}_{\text{curr}}$, $\mathbf{d}$, $\tilde{t}$, t_f

Output: $\mathbf{q}^*$

0) $\mathbf{q}_0 \leftarrow \mathbf{q}_{\text{curr}}$, $\mathbf{q}_{\text{f}} \leftarrow \mathbf{q}_{\text{eng}}$, $t_0 \leftarrow 0$, $\tilde{t}_{phase2}$
1) Calculate $\mathbf{q}(\tilde{t} + \Delta t)$ from a cubic polynomial:
   $\mathbf{q}(t) = \mathbf{q}_0 + \frac{3}{{t_f}^2}(\mathbf{q}_f - \mathbf{q}_0)t^2 - \frac{2}{{t_f}^3}(\mathbf{q}_f - \mathbf{q}_0)t^3$
2) AVM restricts the target joint angles:
   $\mathbf{q}^* \leftarrow \mathbf{q}(\tilde{t} + s\Delta t)$
3) $\tilde{t} \leftarrow \tilde{t} + s\Delta t$

The proposed strategy is engaged when the minimum distance between human and robot $||\mathbf{d}||$ is less than a threshold D_{eng} and the factor provided by AVM is less than a threshold F_{eng}. These conditions trigger *TakeOut*.

At each time interval Δt, *TakeOut* summarizes the contributions of the forces exerted by the human $\mathbf{F}^{\text{human}}$ and by a parking position $\mathbf{F}^{\text{parking}}$ into a resulting force $\mathbf{F}$. From such force $\mathbf{F}$, it calculates a velocity vector $\mathbf{V}'$ to modify the current end-effector velocity. Then it will output the target joint angles that make the end-effector move to a safer location. Such target joint angles are audited by AVM according to the current interaction constraints. The entire algorithm of *TakeOut* is described in the Algorithm 1.

The end of *TakeOut* and, hence, the beginning of *PlaceBack*, occurs when at least one the following conditions is met:

- i) The minimum distance $||\mathbf{d}||$ is greater than a threshold D_{diseng}.
- ii) The displacement of the end-effector is greater than a threshold $D_{withdrawing}$.
- iii) The end-effector reaches the parking position.

At each time interval Δt, *PlaceBack* calculates the corresponding target angle values of a trajectory that moves the

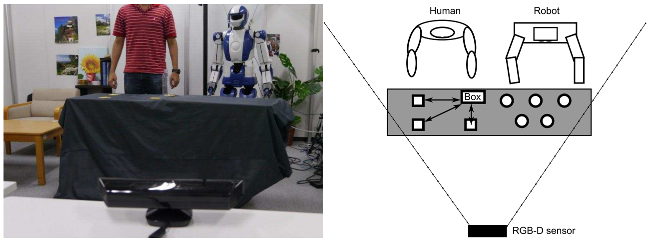

Fig. 4. Left: experimental setup with a humanoid robot and a human subject. Right: schematics of the corresponding tasks.

end-effector from the safer location achieved by *TakeOut*, to the location where the Withdrawal strategy was engaged so that the robot can resume its task. To do this, we use a simple cubic polynomial. In order to complete the trajectory, the algorithm maintains an internal time $\tilde{t} \in [0, t_f]$, which is updated with the Δt scaled by AVM, i.e., $s\Delta t$.

Therefore, from the outline of the *PlaceBack* algorithm, it is evident that the whole motion produced by this phase is also audited by AVM according to the current interaction constraints. The algorithm of *PlaceBack* is described in the Algorithm 2.

IV. EXPERIMENTS

A. Setup

The experiments were carried out using the humanoid robot HRP-4 [11] and a human subject. The distance between human and robot has calculated using the 3D information provided by an RGB-D sensor. We placed both human and robot side by side, both facing the RGB-D sensor. In front of them we placed a table on which both carried out their corresponding tasks. In front of them we placed a table on which both carried out their corresponding tasks, as shown in Fig. 4(left).

In a similar way to [2], we use three components to implement our system: a *trajectory player*, a *safety evaluator* and a *distance estimator*. The first two are implemented using the OpenRTM platform[1], and the last one is implemented using the *Kinect for Windows SDK* version 1.5.

The task of the robot consisted of randomly placing the right hand (the hand closer to the human) in one of five possible locations above the table. In each experiment, the robot randomly places the right hand 30 times.

The task of the human consisted of positioning his left hand (the hand closer to the robot), in four different locations on the table. In one of these locations (the one closer to the robot) there was a box where the human placed the objects that he picked up from the other three locations. Therefore, the human was requested to pick up an object from one of the locations and put it in the box, then pick up another object from the following location, and so on, as shown in Fig. 4(right). The human did such a task for as long as the robot was performing his corresponding task. By doing this, we recreated a simple scenario of a humanoid robot working next to a human doing independent tasks.

[1]"OpenRTM-aist," `http://www.openrtm.org`

Moreover, the human movement, from picking up an object until placing it in the box, was requested to be performed using a metronome, which limited the speed of the human. The idea of limiting the speed of the human task is to try to prevent that the human moves away from or towards the robot, whether intentionally or unintentionally. This is because an anticipated motion of the human could create a bias in the task completion time since the human can deliberately force the robot to move more slowly (or even trigger Withdrawal) by remaining too close, or, on the contrary, avoid staying too close to the robot and, therefore, allow it to move with less restrictions.

B. Results

In order to verify the performance of Withdrawal strategy, we compared it to other three methods: Zeromax, Velocity Moderation (VM), and AVM. We consider Zeromax as a conventional method because it makes the robot stop when the human enters its workspace. The VM method considers only the distance in order to linearly restrict the speed of the robot. Zeromax and VM can be considered as particular cases of AVM. By comparing Zeromax and VM, we validate the effect of a restriction based on a linear decrease of the speed depending on the distance. By comparing VM and AVM, we validate the effect of considering also the direction of the motion and not only the distance.

We consider that the task completion time provides a notion of how much efficiency it is sacrificed in order to preserve safety. Therefore, we evaluate the efficiency of these methods using the task completion time, i.e., the time employed by the robot to complete its task.

A single experiment was to make both human and robot perform their corresponding tasks, using only one method at the time. For each experimental round, we carried four experiments corresponding to the following methods: Withdrawal, AVM, VM, and Zeromax.

Three experimental rounds were done with each subject, for a total of twelve experiments per subject. The experiments were carried out with five subjects.

For all the experiments, we assume that both human and robot can complete the proposed tasks, since such tasks are not shared.

$V_{\rm safe}$ was set to a safe velocity limit of 250[mm/s], as standardized in [12], for the four methods. Also, $D_{\rm max}$ was set to 200[mm], $D_{\rm min}$ to 60[mm], and $F_{\rm rec}$ to 1.0. The results obtained with the experiments are shown in Fig. 5.

Furthermore, we compared the absolute position of both human and robot when using AVM only and when using Withdrawal, to observe the increase in the distance achieved by the proposed method.

When using AVM, the robot comes to a complete stop as the human continues to draw near, as shown in Fig. 6. The resulting distance is too short and the probability of a collision can be naturally considered to be higher.

On the other hand, when using Withdrawal, if the human continues to draw nearer, the robot aims to increase the

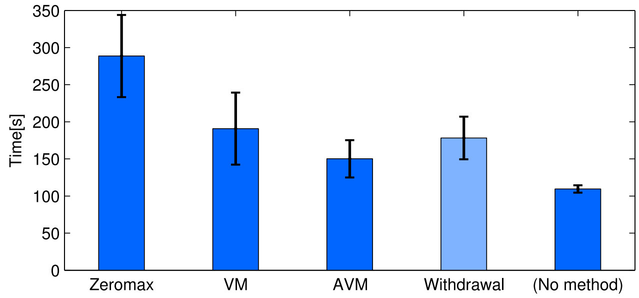

Fig. 5. Task completion time of the compared methods. The proposed method is highlighted.

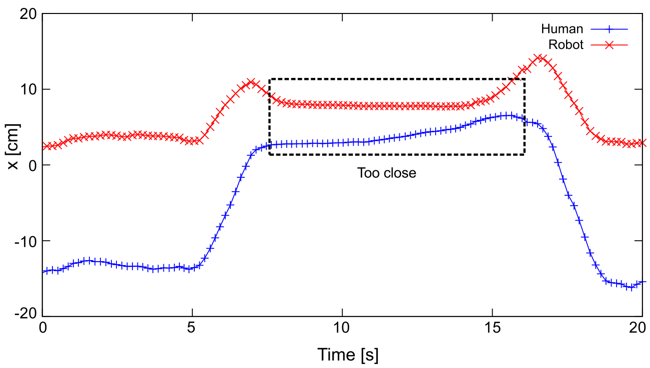

Fig. 6. Plot of x coordinate of the absolute position of human and robot when using AVM.

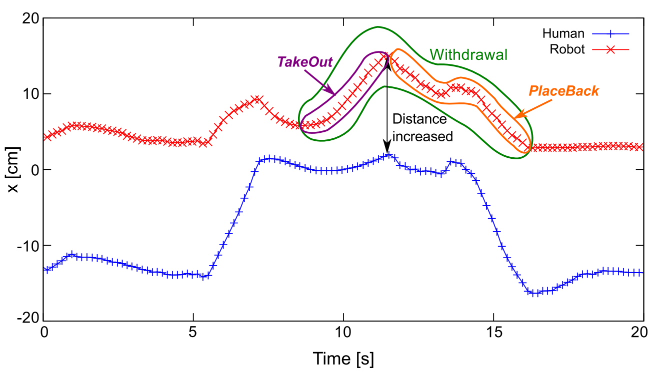

Fig. 7. Plot of x coordinate of the absolute position of human and robot when using Withdrawal.

distance in order to decrease the probability of a collision, as shown in Fig. 7.

V. DISCUSSION

Further experiments are necessary to determine the convergence and stability of the algorithm. The attractive force exerted by the parking position is constant in contrast to the variable and range-dependent repelling force exerted by the human. This aims to make the end-effector converge to the parking position. It is possible to consider that if the parking position force is prevalent, the end-effector will converge to the parking position. Nevertheless, further experiments are necessary to sustain this.

The *PlaceBack* phase consists basically in a third order polynomial that arguably could fail to place the end-effector back to the engage/disengage configuration is some cases. A failure in this phase will obviously compromise the completeness of the task.

Even though the parking position is assumed to be a fixed location, such position could be improved by making it a movable region. This would widen the possible locations where the end-effector can park and would provide safer locations depending on the position/configuration where Withdrawal strategy was engaged.

VI. CONCLUSIONS

We proposed the Withdrawal strategy as a method that aims to increase the minimum distance between human and robot when the current minimum distance is too short. We used a virtual force model to move the robot's end-effector not only away from the human but also to a parking position. We carried out experiments using a human-sized humanoid robot and five human subjects to verify our method. We evaluated the efficiency of the proposed method using the task completion time as a notion of how much efficiency is preserved while guaranteeing human safety. In summary, the test results support the theoretical model that we have proposed.

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