Unfreezing Social Navigation: Dynamical Systems based Compliance for Contact Control in Robot Navigation

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***Abstract*—Soon human-robot interactions in pedestrian areas will be beyond the novelty effect with the deployment of delivery robots, autonomous personal mobility vehicles, and surveillance robots. Proxemics and other social rules guide these interactions, nonetheless, contactless navigation might be yielded infeasible by pedestrian density in certain areas or by adversarial pedestrians. In such scenarios, freezing the robot might go against bystanders safety and task completion might only be feasible under controlled contact interactions. We present a force-limited and obstacle avoidance integrated controller through a time-invariant dynamical system in a closed-loop force controller that let the robot react instantaneously and drive around pedestrians. Mitigating the risk of collision is done by modulating the velocity commands upon detecting a pedestrian and absorbing part of the contact force through active compliant control when the robot bumps inadvertently against the pedestrian.**

I. INTRODUCTION

Guaranteeing obstacle avoidance during navigation in highly occupied areas would be unattainable for current mobile service robots bounded by energy storage capacity, computational resources, and actuation hardware expected to behave as pedestrians, i.e. holonomic, reactive, communicative, and knowledgeable of proxemics and other social rules. Nonetheless, the utility of mobile service robots is getting traction and valuable services such as in-hospital assistance, last-mile deliveries, autonomous cleaning robots and autonomous wheelchairs are becoming popular.

Similarly to what happened with industrial collaborative robots [9, 3], chances are high that one will slowly allow physical contact between mobile robots and humans, especially in crowded environments [11]. Hence, developing control approaches and design requirements to mitigate risks and allow motion control in post-contact between a pedestrian and a service robot should be investigated.

However, most attention has been given to pre-collision planning [2] and human motion prediction [5]. Our goal with this work is to investigate possible post-collision reaction controllers to avoid the ”freezing” robot problem. Especially, considering that collisions would occur within highly dynamic environments such as malls, airports, hospitals, markets, or mix-traffic areas where pedestrians, mobility devices, and even vehicles are frequent. Thus, making a frozen service robot a danger to itself and bystanders [10].

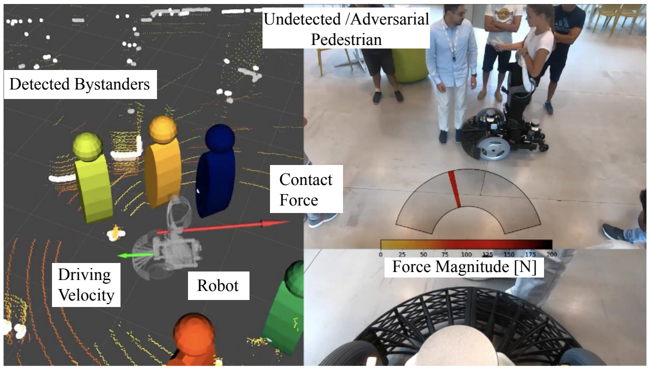

Fig. 1. An adversarial pedestrian colliding with a robot controlled in a single framework of dynamical systems allowing to achieve a sliding response with a constant force around a single obstacle while guaranteeing obstacle avoidance to other obstacles. *Online video demo.*

We designed a controller for our mobile robots that combines online reactivity to obstacle avoidance as provided by dynamical systems-based planners [4] and compliant control using a passive dynamical system approached offered in [6]. Assuming that we have real-time contact sensing in closed-loop control, we enable impedance control for our mobile robot, following our previous approach for explicit force modulation for collaborative environments developed in [1]. Different from these other works, in our formulation the obstacle's exact shape is unknown. Thus, we simplify the problem to assume a single contact point and use the known hull shape of the robot for controlling the desired force during the interaction.

We validate the method on the semi-autonomous standing mobility vehicle Qolo [8] shown in Fig. 1; a type of powered wheelchair for standing mobility of lower-limb impaired people, similar to powered scooters, hoverboards, and unicycles, currently widespread. We tested the approach to validate performance at mitigating contact forces by multiple collisions with a static obstacle varying the initial speed at contact, demonstrating that the robot could perform the sliding control within a set force contact limit.

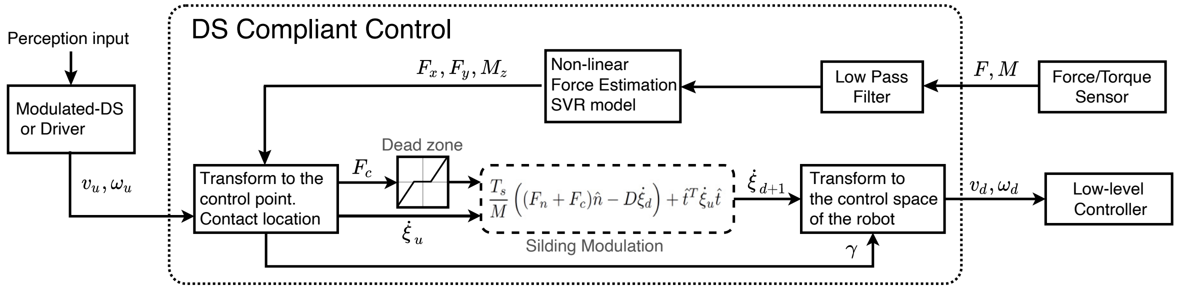

Fig. 2. Compliant controller architecture for a modulated and passive Dynamical System handling the post-collision through sliding.

II. COMPLIANT CONTROL FOR MOBILE SERVICE ROBOTS

Real-life implementations of any obstacle avoidance are bounded by the reactivity of the robot i.e. kinematic and dynamic constraints, actuation power, and highly limited computational resources on mobile robots. Hence, collisions might be rendered unavoidable even in simple scenarios.

We present a compliant response by extending the explicit force control framework in [1] to post-collision, unlike the previous work, the location of the contact surface is unknown a priori, therefore, we make use of a close-loop force control (depicted in Fig. 2) for achieving a sliding control over the surface of the robot while the underlying dynamical system continues to be modulated by the obstacle avoidance in [4] for other agents in the surroundings.

In this formulation for post-collision control, we assumed:

1) Knowledge of the expected contact surface, namely a convex human body part.
2) A collision could occur unexpectedly, thus, distance to the obstacle is unknown a priori.
3) Expected contact occurs at a single location per sensing surface.
4) The operational speed of the robot is slow enough to be safe in the transient phase thus, controllable post-collision.

In Fig. 3 we depicted a linear-DS with the robot represented as a holonomic point-mass (any point in this Cartesian space) and the pedestrian in contact as a convex shape. There are 2 zones of contact with the obstacle represented by: first, a physically impenetrable obstacle (dark grey), and second, a deformable region of the obstacle with a compliant boundary (dotted line) which allows a safe contact force. Finally, we mark a sliding zone (lighter-grey) that represents the volume occupied by the robot during contact around the obstacle. The proposed behaviour was a force bounded sliding contact around the obstacle after entering in contact with the compliant boundary, assuming that there will be a state where the modulated DS will lead away from the contact surface without colliding with other obstacles.

A. Controller Formulation

The robot dynamics was considered as follows:

$$M\ddot{\xi} + C\dot{\xi} = \tau_c + \tau_e \tag{1}$$

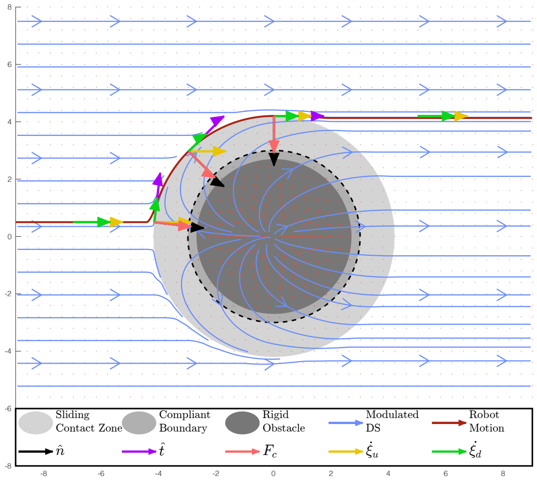

Fig. 3. Sliding DS formulation for limiting contact forces while moving along an underlying desired motion. When the robot enters in contact with the obstacle (light-grey zone) the desired motion is controlled by the reaction force at the boundary guaranteeing a limited contact force F_c to the obstacle and allowing a sliding motion ξ_d around it.

where $\dot{\xi} \in \mathbb{R}^2$ represents the robot's Cartesian velocity as a time invariant position dependent dynamical system. $M \in \mathbb{R}^2$ corresponds to the virtual mass of the robot, $C \in \mathbb{R}^2$ accounts for centrifugal and Coriolis terms, τ_c represents the control forces and τ_e any external disturbances to be rejected. An impedance-DS as proposed in [6] was used to achieve a sliding motion around the obstacle $f(\xi) \in \mathbb{R}^2$ as:

$$\tau_c = \lambda_t f(\xi) - D\dot{\xi} \tag{2}$$

where $D \in \mathbb{R}^2$ represents a state-dependent damping effect. $f(\xi)$ is the dynamical system effectively controlling the robot during contact, composed as: $f(\xi) = f_u(\xi) + f_n(\xi)$, where $f_u(\xi)$ accounts for a force generated by the nominal DS input tangential to the collision surface, and $f_n(\xi)$ describes the force control function as:

$$f_n(\xi) = \frac{F_n + F_c}{\lambda_t}\hat{n} \tag{3}$$

where F_n was chosen a contact force limit bounded by safety and acceptability and F_c the measured contact force. Yielding a controller of the form:

$$\tau_c = \lambda_t f_u(\dot{\xi}) + (F_n + F_c)\hat{n} - D\dot{\xi} \tag{4}$$

Similar limiting force formulation on an impedance controller was shown to be stable even at full-body adversarial humans opposing the robot's motion in [7].

The damping effect on the matrix D was controlled by a normal and tangential parameters over the surface of the obstacle, λ_n and λ_t, respectively.

$$D = Q \begin{bmatrix} \lambda_t & 0 \\ 0 & \lambda_n \end{bmatrix} Q^T \tag{5}$$

where $Q = \begin{bmatrix} \hat{t} & \hat{n} \end{bmatrix}$. In general, by choosing $\lambda_t = 0$ we can provide an undamped free motion along the tangential direction of the collision surface.

Finally, transformation to the velocity domain of the robot was done by a first order Taylor expansion. Thus the control

$$\dot{\xi}_{d+1} = \frac{T_s}{M}\left((F_n + F_c)\hat{n} - D\dot{\xi}_d\right) + \hat{t}^T\dot{\xi}_u\hat{t} \tag{6}$$

This equation allows us to slide over the obstacle while maintaining a constant contact force (F_n), but it does not allow the robot to move away from the obstacle. So, an additional term ($\hat{n}^T\dot{\xi}_u\hat{n}$) was added to $\dot{\xi}_{d+1}$ when the normal vector and underlying dynamical system desired motion oppose each other, herewith, enabling the robot to get away of the obstacle if there underlying DS indicates a feasible free-motion space.

$$\dot{\xi}'_{d+1} = \begin{cases} \dot{\xi}_{d+1} + \hat{n}^T\dot{\xi}_u\hat{n} & \text{if } \left\langle \hat{n}, \dot{\xi}_u \right\rangle < 0 \\ \dot{\xi}_{d+1} & \text{otherwise} \end{cases} \tag{7}$$

The effective velocity (${\dot{\xi}'}_{d+1}$) at the point of contact perpendicular to the surface of the robot is transformed using the Jacobian to the control space of the robot $x = [v, \omega]^T \in \mathbb{R}^2$.

Further inclusion of the obstacle's intended motion could be added in the formulation by defining the state through a differential pose ($\xi = x_r - x_o$). This would make the desired motion $\dot{\xi}_d$ dependent on the obstacle's response, effectively reacting immediately to the obstacle's speed while controlling the desired contact force. Such behaviour requires explicit velocity estimation of the obstacle in contact, however, it could enhance fluid social navigation in interactions with pedestrian flows or other dynamic obstacles.

Fig. 4 depicts an example of robot navigation in 2D around multiple moving obstacles. In this scenario, a linear-DS towards an attractor (green mark) was modulated by the surrounding moving obstacles. This resulting DS acts as the input to the proposed compliant modulation when an "adversarial" obstacle (invisible to the modulation) gets in contact (sensed by penetration and simulated with a constant mass-spring system), which triggers the compliant controller and enables a sliding behaviour around it while avoiding all other moving obstacles.

III. COLLISION SLIDING ASSESSMENT

We evaluated the effects of the operational speed of the robot on the post-collision force response with the proposed controller, to understand the effect of the approach for real-life contact situations. A collision test was set between the mobile robot Qolo [8] and a static object ($80kg$). The contact force limit was set to $F_c = 45N$, while the desired motion ($\dot{\xi}_u$) was set to a linear-DS (ignoring the obstacle) with speeds of $[0.5, 0.75, 1.0]$ m/s.

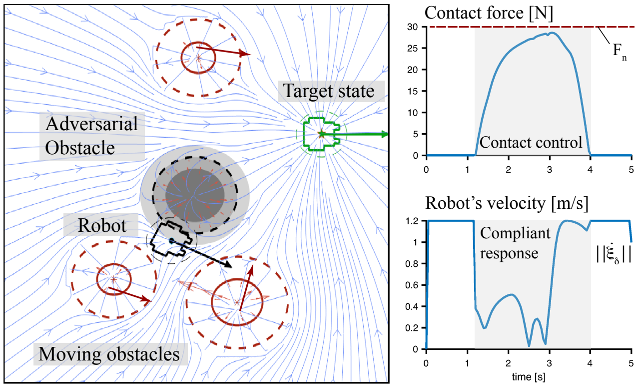

Fig. 4. Sliding Dynamical System coupled with modulated obstacle avoidance example of a pre-collision and post-collision response. Here, multiple moving obstacles were modulated in a linear-DS while an adversarial obstacle collided with the robot, forcing a sliding response while avoiding other obstacles.

Figure 5 presents the maximum contact forces, and the average collision force at various operational speed during two tests per set velocity. We observed a peak collision force increasing with the speed, as expected for the transient force because of the overall delay of the control system. Nonetheless, the average collision force was within a small margin of error (±10 N) for all speeds.

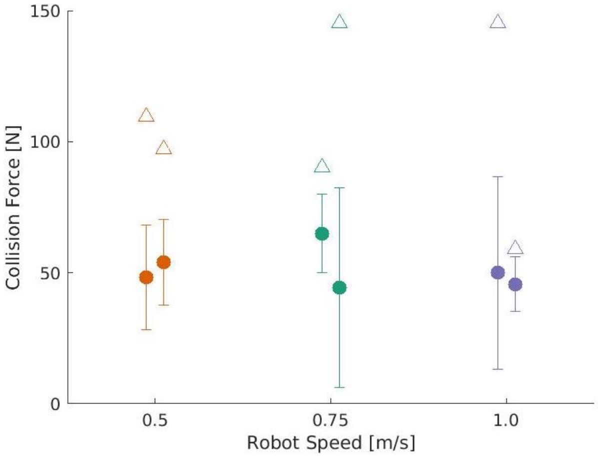

Fig. 5. Resulting change in the maximum post-collision force by changes in the operational speed of the robot.

IV. SUMMARY AND DISCUSSION

We have presented a control method for a mobile service robot to achieve a reactive control on post-collision or during voluntary contact with a pedestrian in highly populated environments, herewith, proposing an alternative solution to the common "safe" approach of freezing a robot if it gets unable to navigate without collision with bystanders.

The proposed approach by a sliding dynamical system around a person presents a continuous solution for modulating the contact forces with a single obstacle and achieve a sliding manoeuvre around it which could be beneficial in tight environments while avoiding contact with other bystanders. Future work should look more closely at how to handle multiple contacts with several people, as well as, investigate how human responses in contact would affect the response of the robot.

Considering social navigation by partially or fully autonomous vehicles brings an inherent risk for communities, and it is an evident political question to raise for each potential application whether its benefits outweigh its risks. Nonetheless, we considered a plausible future where mobile robots will be regulated and certified for entering in "safe" contact with bystanders and the environment when the situation arises.

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