Online minimization of the projected mass of a robot for safe workspace sharing with a human

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***Abstract*—In contexts where a human user and a robot share their workspace, the two major sources of danger for the human are related to impacts where kinetic energy is transferred from the robot to the human body and to quasi-static contacts where contact forces are applied to the human body. In order to reduce the robot kinetic energy while maximizing the robot velocity, a solution consists in minimizing the apparent mass of the robot in direction of the human. Using an online measurement of the relative position of a human and a redundant collaborative robot, the work presented in this paper features a control solution which minimizes the robot apparent mass in direction of the human being while ensuring the task assigned to the robot.**

***Index Terms*—kinetic energy, apparent mass, redundant robot, pHRC**

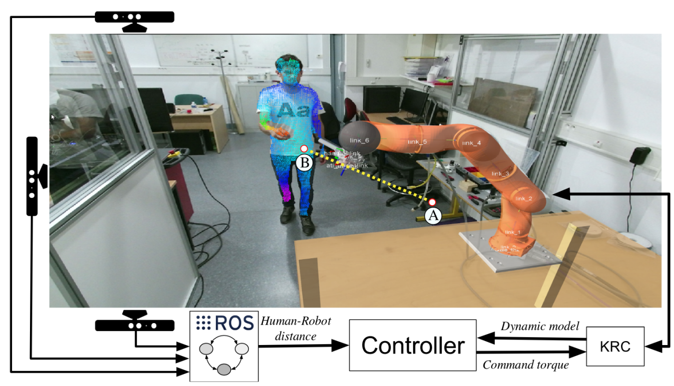

Fig. 1. Scene observed by the RGBD cameras (extracted from [8])

I. Introduction

Human robot collaboration addresses many challenges in terms of safety. When robots perform autonomous motions in an environment shared with humans, one must consider the possible occurrence of undesired contacts. To improve safety, several contributions explore the possibility to avoid contact [1] [2]. However, in constantly evolving environments, contact cannot always be foreseen and avoided. Different control strategies have been proposed to reduce the dangerousness of the contact [3] [4]. If contact has been established, other contributions propose to detect and react to this collision [5].

ISO TS 15066 [6] recommends that during a brief contact with a human, one should prevent the robot from delivering too much kinetic energy. Indeed, this is the energy that will be transferred to the human being. Hence, one must limit the robot kinetic energy at all time to prevent any dangerous contact. From a control point of view this is often dealt with more or less explicitly by monitoring the robot velocity. However, in many applications, the velocity is fixed by the task to realise. Therefore, these solutions reduce the tasks performances for the sake of safety.

In this work, similarly to [7], it is proposed instead to minimize the robot projected mass in the direction of an obstacle. Indeed, this mass plays an important part in the transferred energy in case of contact. This mass is a function of the robot configuration and can be minimized, from a control point of view, if the robot is redundant.

II. Robot projected mass

At each instant, the robot kinetic energy projected in a direction $\boldsymbol{u}$ is

$$e_{c,\boldsymbol{u}} = \frac{1}{2} m_{\boldsymbol{u}} v_{\boldsymbol{u}}^2 \tag{1}$$

with $v_{\boldsymbol{u}}$ and $m_{\boldsymbol{u}}$ respectively the robot velocity and mass projected in the direction $\boldsymbol{u}$. This projected mass is expressed as

$$m_{\boldsymbol{u}}(\boldsymbol{q}) = \boldsymbol{u}^T \left(J(\boldsymbol{q}) M^{-1}(\boldsymbol{q}) J^T(\boldsymbol{q})\right)^{-1} \boldsymbol{u}. \tag{2}$$

where $\boldsymbol{q} \in \mathbb{R}^n$ is the joint space configuration, $M(\boldsymbol{q}) \in \mathbb{R}^{n \times n}$ is the joint-space inertia matrix and $J(\boldsymbol{q}) \in \mathbb{R}^{m \times n}$ is the robot Jacobian matrix for a given task requiring m degrees of freedom. The robot projected mass depends on the robot configuration. For a redundant robot ($m < n$), it is thus possible to find a configuration minimizing this projected mass and thus minimizing the robot kinetic energy in a given direction without influencing the robot main task.

In [9], it is proposed to perform a gradient descent on the projected mass, to determine a new robot configuration which does not influence the main task but minimizes the robot projected mass. This gradient descent can be written

$$\boldsymbol{q}(k+1) = \boldsymbol{q}(k) - \alpha \left(I_n - J(\boldsymbol{q})^{+} J(\boldsymbol{q})\right)^T \boldsymbol{\nabla m_{u}}(\boldsymbol{q}) \Delta t. \tag{3}$$

with $\boldsymbol{q}(k)$, the new robot configuration at the k^{th} iteration of the gradient descent algorithm, J^{+} the Moore-Penrose pseudo-inverse of $J(\boldsymbol{q})$, $\alpha < 1$ a step size and $\boldsymbol{\nabla m_u}$ the gradient of $m_{\boldsymbol{u}}$. The gradient descent algorithm returns a new desired configuration, $\boldsymbol{q}^{des}$, minimizing the robot projected mass without influencing the main task. Given this desired position, it is possible to compute a desired torque to send to reach this configuration

$$\boldsymbol{\tau}_{m_{\boldsymbol{u}}} = k_p(\boldsymbol{q}^{des} - \boldsymbol{q}) - k_d\dot{\boldsymbol{q}}. \tag{4}$$

This desired torque is inserted as a regularisation task inside a Quadratic Programming problem as described in [3].

In [7], this gradient descent is performed to minimize the robot projected mass along the direction of motion of the robot. In this work, it is rather proposed to perform this minimization in the direction of the closest human.

III. Setup

The algorithm presented in section II is tested on a 7 degrees of freedom LWR 4+ KUKA robot. RGBD cameras are used to capture the position of a human. The RGBD cameras are calibrated and their position towards the robot are known. Three cameras are used to avoid any occlusion during the interaction with the robot. The obtained point clouds are merged to obtain a single point cloud representing the human position relatively to the robot. This position is used to compute the direction of the human towards the robot $\boldsymbol{u}$. The whole setup is the one described in [8] and depicted in Figure 1.

IV. Results

In the following experiment, the robot is required to keep a Cartesian pose while a human moves around it. The experiment shows the robot projected mass with and without the projected mass minimization algorithm. For both experiments, the human-robot distance, d, is recorded. The angle, θ, between the direction $\boldsymbol{u}$ and the unit vector $[0, 1, 0]^T$ is computed. During the two experiments, the human performs similar motions around the robot.

Figure 2 depicts the results of this experiment. During the first part of the experiment (Figure a.), the robot projected mass ranges between 2.6 kg and 4.3 kg. In the second part of the experiment (Figure b.), it can be seen that for the same motions of the human around the robot, its projected mass in the direction of the human ranges between 2.5 kg and 2.8 kg which represents an improvement of up to 38%.

The regularisation task can thus be used to minimize the robot perceived mass. Using external sensors it is possible to minimize the perceived mass in the direction of the closest human.

V. Conclusion

Working in collaboration with robots requires considering the possible occurrence of a contact. To prevent any dangerous contact, traditional control solutions propose to reduce the robot velocity when a human is too close. In this work it is shown that it is also possible to adapt the robot configuration to minimize its projected mass and thus its kinetic energy in the direction of contact. If a contact occurs, it is the direction where the most kinetic energy will be transferred between the robot and the human. It allows to use the robot at its maximal velocity before reaching its maximum allowed kinetic energy as recommended by ISO TS15066.

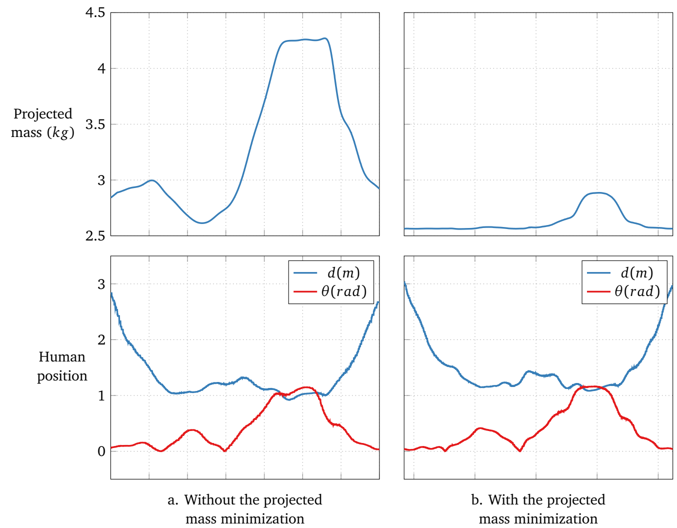

Fig. 2. Reconfiguration of the robot to minimize its perceived mass in the direction of a human. a. shows the projected mass for a given configuration of the robot when the human moves around it. b. shows the projected mass for the same human motion but with the active reconfiguration of the robot to minimize the projected mass.

References

[1] Fabrizio Flacco, Torsten Kroeger, Alessandro De Luca, and Oussama Khatib. A Depth Space Approach for Evaluating Distance to Objects. *Journal of Intelligent & Robotic Systems*, 80(1):7–22, 2014.

[2] Oussama Khatib. Real time obstacle avoidance for manipulators and mobile robots. In *IEEE International Journal of Robotics and Research*, pages 90–98, 1986.

[3] Lucas Joseph, Vincent Padois, and Guillaume Morel. Towards X-ray medical imaging with robots in the open: safety without compromising performances. *IEEE International Conference on Robotics and Automation (ICRA)*, 2018.

[4] Heinzmann; Jochen and Alexander Zelinsky. Quantitative Safety Guarantees for Physical Human – Robot Interaction. *The International Journal of Robotics Research*, 22(7):479–504, 2003.

[5] S. Haddadin, A. De Luca, and A. Albu-Schäffer. Robot collisions: A survey on detection, isolation, and identification. *IEEE Transactions on Robotics*, 33(6):1292–1312, 2017.

[6] ISO/TS-15066. *Robots and robotic devices - Collaborative robots*. International Organization for Standardization, Geneva, Switzerland, 2016.

[7] Nico Mansfeld, Badis Djellab, Jaime Rald, Fabian Beck, Christian Ott, and Sami Haddadin. Improving the Performance of Biomechanically Safe Velocity Control for Redundant Robots through Reflected Mass Minimization. In *IEEE International Conference on Intelligent Robots and Systems*, pages 5390–5397, 2017.

[8] A. Meguenani, V. Paddois, J. Da Silva, A. Hoarau, and P. Bidaud. Energy-based control for safe human-robot physical interactions. In *International Symposium on Experimental Robotics*, pages 809–818, 2017.

[9] Vincent Padois, Pascale Chiron, and Jean-Yves Fourquet. Controlling dynamic contact transition for nonholonomic mobile manipulators. In *International Conference on Intelligent Robots and Systems*, pages 3817–3822, 2004.