Using a legged manipulator for nonprehensile object transportation

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***Abstract*— This paper tackles the problem of nonprehensile object transportation through a legged manipulator. A whole-body control architecture is devised to prevent sliding of the object placed on a tray-like end-effector and retain the legged robot balance during walking. The controller solves a quadratic optimization problem to realize the sought transportation task while maintaining the contact forces between the tray and the object and between the legs and the ground within their respective friction cones.**

Paper Type **– Recent Work [1]**

I. Introduction

In the last years, more and more robots have been developed to assist humans not only during dangerous and exhausting tasks but also for domestic applications and care assistance [2], [3]

To perform all of these different applications, the research has been directed toward mobile manipulators that can traverse large spaces and execute manipulation tasks.

Most mobile robots developed in the last years are wheeled robots endowed with one or two arms to enable them to perform manipulation tasks [4], [5]. However, wheeled robots often encounter difficulties in unstructured environments with non-flat grounds, while legged robots can overcome these obstacles. Indeed, they can move in sites where wheeled robots could remain stuck

Although their performance can exceed those of wheeled robots in certain situations, legged robots still need to find their space in the real world. To widen their spectrum of applications, the recent trend is to endow multi-legged robots with arms that make them capable of grasping and manipulating objects [6].

Despite their unique features, legged robots have rarely shown nonprehensile manipulation skills. This kind of manipulation can be considered one of the most complex task [7] since it is neither possible to prevent infinitesimal motions of the object nor to resist all the external wrenches applied to it.

This paper aims to propose an approach that allows legged robots to perform nonprehensile manipulation tasks. Indeed, endowing these robots with this capability would enable them to perform a broader range of dexterous manipulation tasks, which are critical in the field of service robotics.

Carrying a payload modifies the robot's dynamics, and the controller needs to account for both locomotion and

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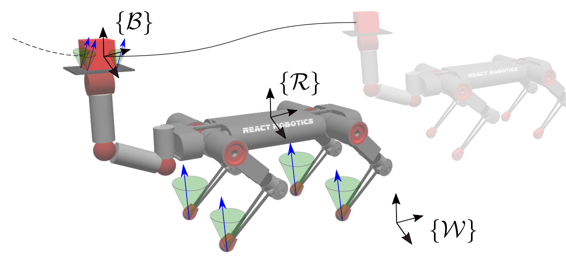

Fig. 1. A legged manipulator has to transport an object (red cube) placed on a tray-like end-effector along a trajectory (black) from a starting configuration (transparent) while simultaneously preventing its sliding by keeping contact forces (blue) inside the friction cones (green).

manipulation tasks. Some controllers handle these tasks separately [8]. Differently, some whole-body controllers were realized to handle locomotion and manipulation tasks altogether [6], [9]. However, to the authors' knowledge, only in our work [1] a legged robot transporting an object in a nonprehensile configuration has been considered. When the robot does not firmly grasp an object, there exist motions induced by inertial or external forces that can not always be inhibited [10]. In such a case, the object can still be manipulated, typically realizing a sequence of opportunely combined nonprehensile manipulation primitives [7], [11]. In this work the so-called dynamic grasping (or nonsliding) manipulation primitives are employed, which immobilizes the object to the robot palm by exploiting gravity, inertial, and frictional forces.

For this reason, the proposed framework needs to satisfy non-sliding constraints for both the object and the feet of the robot. Differently from [12], these constraints are addressed in a unified and principled way through an optimization-based whole-body controller for a legged robot transporting an object on a tray in a nonprehensile configuration.

II. System Model

A. Transported object

The object dynamics must be taken into account to deal with the transportation problem. To model the dynamics of an object transported by a tray-like end-effector mounted onto a robotic platform, the assumptions introduced in [12] can be considered. Let $q_b = (p_b, R_b) \in SE(3)$ be the pose of the object frame $\{\mathcal{B}\}$ (Fig. 1) attached to the object's center of mass (CoM). The object dynamics can be written as

$$M_b\dot{\mathcal{V}}_b + C_b(\mathcal{V}_b)\mathcal{V}_b + N_b(R_b) = \mathcal{F}_b, \tag{1}$$

The definition of all the matrices and vectors can be found in [1]. The body wrench $\mathcal{F}_b$ is dictated by the tray/object contact forces. Given the assumptions in [1], the number of contact points is $n_c = 4$, corresponding to the vertexes of the cube facing the tray. A suitable contact model is adopted to control the tray/object interaction behaviour [1]. Let consider the stacked vector $F_c = \left[f_{c_1}^{\mathrm{T}}, ..., f_{c_{n_c}}^{\mathrm{T}}\right]^{\mathrm{T}} \in \mathbb{R}^{3n_c}$, containing the linear contact forces $f_{c_i} \in \mathbb{R}^3$ at the i-th contact point. To obtain a safe object transportation, each contact force vector $f_{c_i} \in \mathbb{R}^3$ must be contained inside the $i-$th friction cone FC_i. The $i-$th friction cone can be defined as the set of generalized contact forces realizable given the friction coefficient μ, between the object and the tray. This constraint can be expressed in linear form by approximating the i-th friction cone with a polyhedral cone generated by a finite set of unit vectors $\hat{f}_{c_i,j} \in \mathbb{R}^3$. The number of unit vectors $k \in \mathbb{N}_{>0}$ that constitute the approximated friction cone's edges is chosen as $k = 4$ in this work [12]. The constraint is formulated expressing f_{c_i} as a non-negative linear combination of unit vectors $\hat{f}_{c_i,1}...\hat{f}_{c_i,k} \in \delta FC_i$, with δFC_i denoting the boundary of the i-th cone manifold, i.e., $FC_{c_i} = \left\{ f_{c_i} \in \mathbb{R}^3 : f_{c_i} = \sum_{j=1}^{k} \lambda_{c_i,j} \hat{f}_{c_i,j}, \quad \lambda_{c_i,j} \geq 0 \right\}$.

By denoting $\Lambda_b = \left[\lambda_{c_{1,1}}, ..., \lambda_{c_{n_c,k}}\right] \in \mathbb{R}^{kn_c}$ and $\hat{F}_c = \mathrm{blockdiag}(\hat{F}_{c,1}, ..., \hat{F}_{c,n_c})$, with $\hat{F}_{c,i} = \left[\hat{f}_{c_i,1}, ..., \hat{f}_{c_i,k}\right]$, the stacked vector of contact forces can be compactly rewritten as $F_c = \hat{F}_c \Lambda_b$. When a non-sliding behaviour is desired it is sufficient to impose $\Lambda_b \geq 0$ to constrain all the contact forces inside the respective cones. This approach has demonstrated good performance with real hardware [12]. It can be noticed that the shape and the dynamics of the object are supposed to be known. In the case of an unknown object, the problem becomes more complicated. However, these challenges regard the non-prehensile robotics instead of the legged one. For this reason, they are considered out of the scope of this paper.

B. Legged robot manipulator

A legged robot endowed with a robotic arm can be described as a free-floating base with the legs and the arm attached. The free-floating base is usually modelled through six virtual joints giving six degrees of freedom (DoFs) in a world frame. Since the position of the robot's CoM is crucial for balancing, the dynamic model of a legged robot can be formulated in terms of the global CoM through the transformation introduced in [13]. Let $q_r = (p_r, R_r) \in SE(3)$ be the pose of a frame whose position is attached to the robot's CoM and whose orientation is the one of a fixed frame on the main body, and let $q \in \mathbb{R}^n$ be the vector collecting the arm and legs' joints. The legged system dynamics equipped with an arm can be written as

$$\begin{bmatrix} M_{com}(q) & O_{6\times n} \\ O_{n\times 6} & M_q(q) \end{bmatrix} \dot{\upsilon} + \begin{bmatrix} O_{6\times 6+n} \\ C_q(q,\upsilon) \end{bmatrix} \upsilon + \begin{bmatrix} m_r g \\ 0_n \end{bmatrix} = \begin{bmatrix} 0_6 \\ \tau \end{bmatrix} + \begin{bmatrix} J_{st,com}(q)^{\mathrm{T}} \\ J_{st,j}(q)^{\mathrm{T}} \end{bmatrix} F_{gr} + \begin{bmatrix} J_{com}(q)^{\mathrm{T}} \\ J_q(q)^{\mathrm{T}} \end{bmatrix} F_{ext} + \begin{bmatrix} J_{r,com}^{b}(q)^{\mathrm{T}} \\ J_{r,j}^{b}(q)^{\mathrm{T}} \end{bmatrix} F_c, \tag{2}$$

The definition of all the matrices and vectors can be found in [1]. The same contact model presented in II-A is used to represent the ground reaction forces as $F_{gr} = \hat{F}_{gr}\Lambda_{gr}$, with $\Lambda_{gr} = \left[\lambda_{gr_{1,1}}, ..., \lambda_{gr_{n_{st},k}}\right] \in \mathbb{R}^{kn_{st}}$ and $\hat{F}_{gr} = \mathrm{blockdiag}(\hat{F}_{gr,1}, ..., \hat{F}_{gr,n_{st}})$, with $0 < n_{st} \leq n_l$ the number of stance legs and n_l the number of legs, and $\hat{F}_{gr,i} = \left[\hat{f}_{gr_i,1}, ..., \hat{f}_{gr_i,k}\right]$, describing the friction cone manifold, considering μ_{gr} the friction coefficient of the floor. As for the object problem, to have a nonsliding behaviour of the feet and retain the balance, it must be $\Lambda_{gr} \geq 0$ to constrain the forces inside the cones.

III. Optimization-based Controller

The addressed problem is to transport the object placed on a tray-like end-effector to the desired pose following the desired trajectory, preventing the object from sliding and retaining the robot's balance during the motion. To achieve this goal, a whole body controller is proposed, composed of a motion planner and an optimization problem. Moreover, the momentum-based observer presented in [14] is included in the framework to reject external disturbances.

A. Motion planner

The motion planner computes the references for the object, the CoM, and the swing feet inside the quadratic problem. The way it computes all these references is described in [1]

B. Quadratic problem

The optimization problem employs centroidal and object dynamics to track the floating base and object motion references, respectively. The chosen vector of control variables is $\zeta = \left[\dot{\upsilon}^{\mathrm{T}} \quad \Lambda_{gr}^{\mathrm{T}} \quad \Lambda_b^{\mathrm{T}}\right]^{\mathrm{T}} \in \mathbb{R}^{n_v}$, with $n_v = 6+n+kn_{st}+kn_c$. The problem, further described in the following, has the following form

$$\underset{\zeta}{\mathrm{minimize}} \quad f(\zeta) \tag{3}$$

$$\text{subject to} \quad A\zeta = b, \tag{4}$$

$$D\zeta \leq c. \tag{5}$$

1) Cost Function $f(\zeta)$: The problem aims at tracking both the CoM's reference and the object's reference. Let consider the desired wrench at the robot's CoM $\mathcal{F}_{com,ref}$ and the desired body wrench $\mathcal{F}_{b,ref}$ for the object, whose expression is defined in [1]. Considering $\hat{F}_{ext}$ the estimation of the momentum-based observer integrated in the framework, it can be split into $\hat{F}_{st} \in \mathbb{R}^{3n_{st}}$, regarding the support legs, and $\hat{F}_{sw} \in \mathbb{R}^{3(n_l-n_{st})}$, regarding the swing legs. The optimization can be defined as a multi-objective quadratic problem, with two objective functions aiming to track the desired wrench at the robot's CoM and the desired wrench at the object's CoM, respectively

$$f_1(\zeta) = \left\| J_{st,com}^{\mathrm{T}} \hat{F}_{gr} \Sigma_1 \zeta + J_{st,com}^{\mathrm{T}} \hat{F}_{st} - \mathcal{F}_{com,ref} \right\|_{Q_1}, \tag{6}$$

$$f_2(\zeta) = \left\| G \hat{F}_c \Sigma_2 \zeta - \mathcal{F}_{b,ref} \right\|_{Q_2}, \tag{7}$$

with $\|\cdot\|_{\times}$ the quadratic form with proper matrix. Considering (6) and (7), a full cost function $f(\zeta)$ can be defined as in [1].

2) Equality constraints $A\zeta = b$: Three equality constraints need to be imposed. The first one constraints the control variable to be consistent with (2)

$$\begin{bmatrix} M_{com}(q) & O_{6\times n} & -J_{st,com}(q)^{\mathrm{T}}\hat{F}_{gr} & -J^{b}_{r,com}(q)^{\mathrm{T}}\hat{F}_{c} \end{bmatrix}\zeta = \\ = -m_r g. \tag{8}$$

The second one guarantees that the contact of the stance feet is maintained, imposing their velocity equal to zero as $J_{st}(q)\upsilon = 0_{3n_{st}}$, whose time derivative can be written as

$$\begin{bmatrix} J_{st}(q) & O_{3n_{st}\times kn_{st}} & O_{kn_{st}\times kn_{c}} \end{bmatrix}\zeta = -\dot{J}_{st}(q,\dot{q})\upsilon. \tag{9}$$

The third constraint imposes the velocity at the arm's end-effector in order to track the desired object motion

$$\begin{bmatrix} J^{b}_{b}(q) & O_{6\times kn_{st}} & O_{6\times kn_{c}} \end{bmatrix}\zeta = -\dot{J}^{b}_{b}(q)\upsilon + \dot{\mathcal{V}}_{b,ref}. \tag{10}$$

Collecting (8), (9), and (10) yields defining the terms A and b in (4), omitted for brevity.

3) Inequality constraints $D\zeta \leq c$: Ground reaction forces and object/tray contact forces must be constrained to guarantee the nonsliding behaviour

$$\Lambda_{c,i} \geq 0 \qquad \Lambda_{gr,i} \geq 0. \tag{11}$$

For mechanical and safety reasons, joint torques need always to be limited. Being $\tau_{min}, \tau_{max} \in \mathbb{R}^n$ the minimum and maximum reachable torques, respectively, the constraints about limited torques can be expressed as follows

$$\begin{aligned} &\tau_{min} - C_q(q,\upsilon)\,\dot{q} \leq \\ \begin{bmatrix} O_{n\times 6} & M_q(q) & -J^{\mathrm{T}}_{st,j}(q)\,\hat{F}_{gr} - J^{b\mathrm{T}}_{r,j}(q)\,\hat{F}_c \end{bmatrix}&\zeta \leq \\ &\tau_{max} - C_q(q,\upsilon)\,\dot{q}. \end{aligned} \tag{12}$$

Finally, an equality constraint should be imposed to track the desired trajectory for the swing feet, as can be seen in [14]. This constraint is softened by adding slack variables γ. The addressed inequality constraint is chosen as [14]

$$\ddot{x}_{sw,cmd} - \gamma \leq J_{sw}(q)\dot{\upsilon} + \dot{J}_{sw}(q,\dot{q})\upsilon \leq \ddot{x}_{sw,cmd} + \gamma. \tag{13}$$

Therefore, collecting (11), (12), and (13), the terms c and D in (5) are retrieved, but they are here omitted for brevity.

4) Control torque: Given the result of the optimization problem, the control torques can be computed as $\tau = M_q(q)\ddot{q} + C_q(q,\upsilon)\dot{q} - J_{st,j}(q)^T\hat{F}_{gr}\Lambda_{gr} - J^{b}_{r,j}(q)^{\mathrm{T}}\hat{F}_c\Lambda_b$,

IV. Simulation Results

An extensive simulation campaign has been carried out to validate the devised architecture. An analysis of the framework performance, taking into account the variability of the object's parameters can be found in [1].

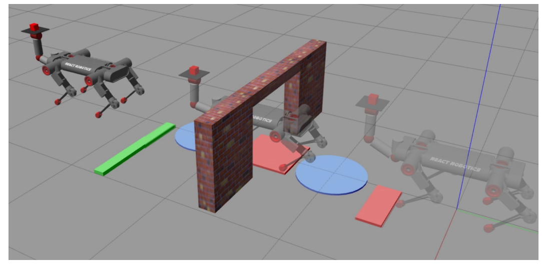

Fig. 2. Simulation setup and executed robot trajectory. Obstacles with different heights and friction coefficients are placed on the ground. A wall with a narrow gap is present along the robot desired path.

A. Simulation

Simulations have been carried out with the Gazebo dynamic simulator (integrated in ROS). The addressed legged system is the DogBot from React Robotics, a quadruped (i.e., $n_l = 4$) open-source platform (see [14] for more details). The quadruped has been endowed with a 6-DoF arm (Fig. 1) inspired by the structure of the HyQ's centaur-like version [8], [15].

The scenario used for testing our framework is shown in Fig. 2. A wall with a narrow gap, whose width and height are 1 m and 0.65 m, respectively, is positioned inside the environment to force the robot to lower itself, showing the capability to also execute vertical movements without compromising the performance. Besides, some blocks have been added to reproduce the terrain's irregularities. With reference to Fig. 2, the heights of the blocks are 0.015 m for the blue, 0.035 m for the green, and 0.02 m for the red one. The friction coefficients are set to 0.4, 0.6, and 0.8, respectively. The ground friction coefficient value is 1. The observer developed in [14] was also used.

Different simulations were performed with varying mass, friction, and dimensions of the transported object. A video presenting the simulations is also available [1] The controller was always successful in preventing the object from sliding and dropping. Besides demonstrating the successful accomplishment of the task, the performance was evaluated considering robustness, tracking error, and smoothness metrics, whose definitions can be found in [1], where a further evaluation of the analysis can be found. However, to summarize, none of the considered factors significantly affect the tracking measure $\mathcal{T}$. This can be attributed to the particular choice of the factor levels and the robot motion parameters. Tracking may be affected when considering a more significant variation of the factors. This will be investigated in future works. Also, it was shown that having a larger μ always increases robustness and smoothness but the value of the object dimension influences this increment. In real scenarios, this result may be used to design tray-like end-effectors with optimized friction coefficients for such tasks accounting for the transported object dimensions. Moreover, it was shown that heavier objects are generally more challenging to be safely carried. This is reflected in the lower robustness and smoothness measures. In this case,

[1] https://youtu.be/eT-N4kTAC8g

optimal trajectory planning and model-based control methods (e.g., variable orientation [12]) may be employed.

V. Conclusion and discussion

A whole-body controller for the nonprehensile transportation of an object through a legged manipulator was presented in this paper. The architecture demonstrated noteworthy performance in simulations performed under different conditions. Besides demonstrating the successful accomplishment of the task, the performance was evaluated considering robustness, tracking error, and smoothness metrics.

The results of the analysis will be the starting point for the development of new trajectory planning and model-based control methods, with the employment of different contact models and refined approximations.

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