Proceedings Paper:

Li, J, Peers, C, Xin, S et al. (1 more author) (2022) Opening a Spring-Loaded Door with a Legged Manipulator. In: UKRAS22 Conference “Robotics for Unconstrained Environments” Proceedings. #UKRAS22: The 5th UK Robotics and Autonomous Systems Conference, 26 Aug 2022, Aberystwyth, UK. EPSRC UK-Robotics and Autonomous Systems (UK-RAS) Network , pp. 16-17.

https://doi.org/10.31256/To1Ke3E

Opening a Spring-Loaded Door with a Legged Manipulator

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***Abstract*—This paper outlines the process of opening a spring-loaded door with a quadrupedal mobile manipulator. A Cartesian trajectory planner based on manifold interpolation is developed to provide designed base and gripper trajectories, and a whole-body controller based on the hierarchical inverse dynamics approach is implemented to enable the robot to cope with unknown external disturbances. The spring-loaded door opening task is successfully achieved in simulation and robust interaction is established without creating undesired forces.**

***Index Terms*—legged manipulator, whole-body control, quadruped robots, spring-loaded door opening**

I. Introduction

In the past decades, disasters such as nuclear leak at the Fukushima Daiichi Nuclear Power Plant have highlighted the real need of robotic systems for effective disaster responses. This leads to practical robotics research which aims to perform dangerous tasks for humans. Among a large set of real world tasks, the door opening task is usually considered as a typical scenario as it requires the robot not only to traverse, but also to interact with the unknown environment designed for humans. Without a doubt, opening a spring-loaded door with a spring-loaded handle is the most challenging.

Several solutions on the door opening using legged robots have been presented in the past few years. A task-prioritized impedance control (MPC) framework was proposed for a humanoid robot with a dual-arm which can safely interact with the normal door with a spring-loaded handle [1]. A unified model predictive control framework enables a quadrupedal mobile manipulator to open a spring-loaded door without handle [3]. A legged mobile manipulator performed dynamic locomotion while opening a spring-loaded door with a spring-loaded handle [2].

The key challenges in a spring-loaded door opening task mostly stem from the geometrical constraint of maintaining contact with the door and the unknown resistances created by the door and the handle, which may cause unachievable kinematic requirements and larger internal forces generated between the robot and door. Fortunately, the interpolation method on manifold [4] has been proposed, which can be used to generate orientation trajectories with minimum acceleration, and the recently developed task-space inverse dynamics approach [5], [6] can be used to cope with unknown disturbances.

In this paper, a Cartesian trajectory planner is developed based on manifold interpolation, and a whole-body controller based on the hierarchical inverse dynamics approach is implemented for a quadrupedal mobile manipulator, which enables the user to control the gripper and robot base simultaneously to open a spring-loaded door and walk pass.

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This work was supported by the Engineering and Physical Sciences Research Council [grant numbers EP/V026801/2, EP/R513258/1-2441459] and the AMPI [Innovate UK project number 84646].

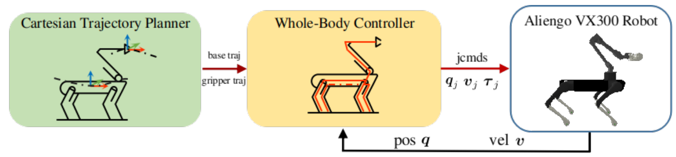

Fig. 1. A schematic diagram depicting the components of the full control architecture designed for the legged mobile manipulator *Aliengo VX300* to open a spring-loaded door.

II. System Overview

The robot used in this work is the *Aliengo VX300* robot [7], an accurately torque-controlled *Aliengo* robot created by Unitree, equipped with a five degree-of-freedom robotic arm *ViperX 300* from Trossen Robotics. The control architecture shown in Fig. 1 is comprised of a Cartesian trajectory planner and a whole body controller. The trajectory planner is responsible for generating trajectories of the gripper and robot base. To track these Cartesian trajectories, the whole body controller generates desired generalised accelerations and external forces by solving a hierarchical quadratic programming (HQP) problem, then calculates joint torque, velocity and position commands of each joint from them.

III. Cartesian Trajectory Planning

Given the current position of the robot and the geometry of the door obtained from the simulator or the perception system of the real robot, a series of key points of the robot base and gripper trajectories can be chosen to avoid collisions. Between two adjacent poses, the interpolation method on SE(3) manifold can be used to generated the whole trajectory.

In detail, to generate the trajectory from the start pose ${}^W\boldsymbol{X}_{start} = \left({}^W\boldsymbol{R}_{start}, {}^W\boldsymbol{p}_{start}\right)$ at t_{start} time to the end pose ${}^W\boldsymbol{X}_{end} = \left({}^W\boldsymbol{R}_{end}, {}^W\boldsymbol{p}_{end}\right)$ at t_{end} time, the time scaling $s(t)$ can be expressed with a cubic polynomial of time,

$$s(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3, \quad t \in [t_{start}, t_{end}], \tag{1}$$

and the interpolated pose can be computed with

$$\begin{aligned} {}^W\boldsymbol{p}(s) &= {}^W\boldsymbol{p}_{start} + s\left({}^W\boldsymbol{p}_{end} - {}^W\boldsymbol{p}_{start}\right), \\ {}^W\boldsymbol{R}(s) &= {}^W\boldsymbol{R}_{start} \exp\left(\log\left({}^W\boldsymbol{R}_{start}^T\, {}^W\boldsymbol{R}_{end}\right) s\right). \end{aligned} \tag{2}$$

Equation (2) decouples the rotational motion from the translational motion to ensure that the frame origin follows a straight line. The pose trajectory can also be generated with

$$\boldsymbol{X}(s) = {}^W\boldsymbol{X}_{start} \exp\left(\log\left({}^W\boldsymbol{X}_{start}^{-1}\, {}^W\boldsymbol{X}_{end}\right) s\right), \tag{3}$$

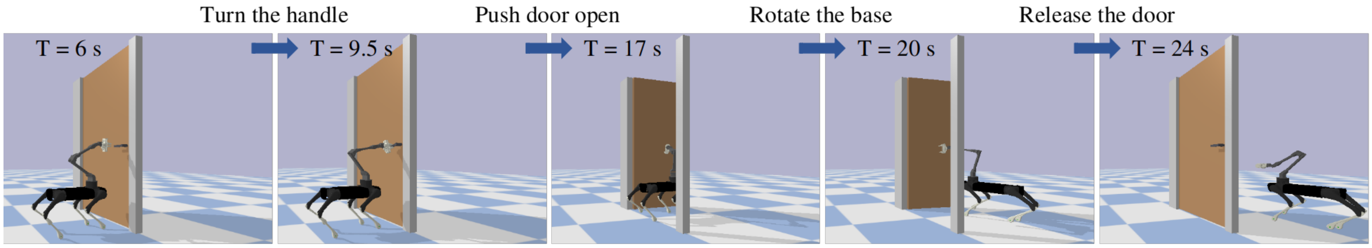

Fig. 2. Snapshots of the robot opening a spring-loaded door and walking pass.

which generates a screw motion providing a "straight-line" motion in the sense that the screw axis is constant. It is worth mentioning that the straight-line in screw motion do not yield straight-line motion of the frame in task space.

IV. Whole-Body Control

The inverse dynamics approach accounts for system dynamics, manipulates contact forces to control the floating base and transforms task space references into joint space commands. The approach can be divided into two processes.

The first process finds the optimal generalised accelerations $\dot{\boldsymbol{v}}$ and external forces $\boldsymbol{\lambda}$ by solving the optimisation problem:

$$\begin{aligned} \min_{\boldsymbol{X}} \quad & \frac{1}{2}\boldsymbol{X}^T\boldsymbol{Q}\boldsymbol{X} + \boldsymbol{p}^T\boldsymbol{X} \\ s.t. \quad & \begin{bmatrix} \boldsymbol{C}_{p+1}\bar{\boldsymbol{N}}_p & -\boldsymbol{I} \\ \bar{\boldsymbol{C}}_p\bar{\boldsymbol{N}}_p & \boldsymbol{0} \end{bmatrix} \boldsymbol{X} \leqslant \begin{bmatrix} \boldsymbol{d}_{p+1} - \boldsymbol{C}_{p+1}\bar{\boldsymbol{x}}_p^* \\ \bar{\boldsymbol{d}}_p - \bar{\boldsymbol{C}}_p\bar{\boldsymbol{x}}_p^* + \bar{\boldsymbol{s}}_{in,p}^* \end{bmatrix}, \end{aligned} \tag{4}$$

where the equivalent optimisation variable $\boldsymbol{X} = \begin{bmatrix}\boldsymbol{x}^T & \boldsymbol{w}^T\end{bmatrix}^T$ collects the optimisation variable $\boldsymbol{x} = \begin{bmatrix}\dot{\boldsymbol{v}}^T & \boldsymbol{\lambda}^T\end{bmatrix}^T$ and slack variable $\boldsymbol{w}$. $\boldsymbol{Q}$ and $\boldsymbol{p}$ can be computed from stacked task coefficients $\bar{\boldsymbol{A}}_p$, $\bar{\boldsymbol{b}}_p$, $\bar{\boldsymbol{C}}_p$ and $\bar{\boldsymbol{d}}_p$. Please refer to [8] for detailed explanation and implementation.

Then, the second process calculates joint torques for the legged manipulator from optimised generalised accelerations $\dot{\boldsymbol{v}}$ and external forces $\boldsymbol{\lambda}$ with

$$\boldsymbol{\tau} = \boldsymbol{M}_a(\boldsymbol{q})\dot{\boldsymbol{v}} + \boldsymbol{h}_a(\boldsymbol{q}, \boldsymbol{v}) - \boldsymbol{J}_{c,a}^T\boldsymbol{\lambda}, \tag{5}$$

where $\boldsymbol{M}_a$, $\boldsymbol{h}_a$ and $\boldsymbol{J}_{c,a}$ are coefficients of the underactuated part of the equations of motion for the entire robotic system.

V. Simulation

The task of opening a spring-loaded door with a spring-loaded handle is considered to validate the proposed methodology and provide a comprehensive understanding of the whole door opening process.

Fig. 2 presents the process of executing the spring-loaded door opening task, which can be broken down into: turn the handle, push the door open, rotate the base and release the door. During all of the sub-processes, the motions of the base and the gripper are planned and tracked simultaneously instead of considering locomotion and manipulation separately.

Fig. 3 shows the base and gripper trajectories generated by the Cartesian trajectory planner. It can be seen from this graphic that after setting up a series of key points, smooth trajectories for the base and gripper can be generated. It needs

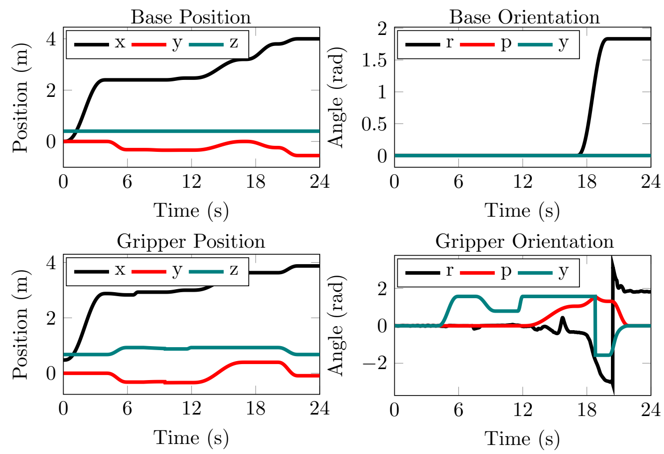

Fig. 3. Planned base and gripper trajectories.

to be clarified that although the base and gripper orientations are described as Euler angles which cause discontinuity phenomenon in the bottom right figure, they are represented as rotation matrices in the planning and control processes, which won't cause singularities issues.

VI. Conclusion

In this work a Cartesian trajectory planner and a whole-body controller have been implemented to enable the quadrupedal manipulator to open a spring-loaded door and walk through it. The effectiveness of the planner and controller have been verified in the spring-loaded door opening task in simulation. The next study will migrate proposed the planner and controller to the real robot *Aliengo VX300*.

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