The Explicit Reference Governor for Real-time Safe Control of a Robotic Manipulator*

Kelly Merckaert[1], Bryan Convens[1], Ilias El Makrini[1], Greet Van der Perre[1], Marco M. Nicotra[2], and Bram Vanderborght[1]

Abstract— **Robotic manipulators that can coexist with humans need formal safety guarantees. Current solutions cannot handle both input and state constraints, reduce the robot capabilities, or are computationally too expensive. To tackle these drawbacks, we analyzed the Trajectory-Based Explicit Reference Governor, which can address both input and state constraints, and does not require any online optimization. We present the methodology for a generic robot arm and show results for the Franka Panda manipulator. The proposed control scheme is able to steer the robot arm to the desired end-effector position, or an admissible approximation, in the presence of limited joint ranges, actuator saturations, and static obstacles.**

I. Introduction

In recent years, manufacturing companies are adopting mass customization strategies. The resulting increased flexibility in the production environment can be obtained by combining the qualities of humans with the qualities of robots [1]. For collaborative robots that are able to work directly in proximity of human operators, the safety issue is of major importance [2].

To obtain safe human-robot coexistence, the typical industrial robot manipulators are re-engineered with passive compliant actuators like Variable Impedance Actuators [3] or by the addition of joint torque sensors [4]. To make the robot's actions more predictable for the human, the robot's motions are made more human-like, but this strategy cannot guarantee safety without the addition of input and state constraints [5].

A randomized kinodynamic path planning approach can be used to handle joint angle limitations in cluttered environments, but computing safe trajectories take too long, making it less suitable for tasks with quickly changing specifications [6]. Kinetostatic safety fields, based on the cumulative danger field and on the repulsive potential field approach, capture the risk in the vicinity of an arbitrary rigid body moving in space, but does not take into account input constraints [7].

In [8] joint angle, velocity, and acceleration constraints together with obstacle constraints are taken into account, but torque constraints are not considered.

Due to recent advancements in computational performances, Model Predictive Control can be implemented on robots to handle both state and input constraints in real-time [9]. However, the application possibilities are limited because of the typically non-negligible computational cost.

We base ourselves on the Explicit Reference Governor (ERG), a closed-form feedback control scheme that can enforce both state and input constraints of nonlinear systems without having to solve an online optimization problem [10]. In [11] the idea was explored on a 2DOF robotic manipulator, here we analyze the methodology on the Franka Panda robot.

II. Trajectory-Based Explicit Reference Governor

Consider the joint space dynamic model of a manipulator

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}}+\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}+\boldsymbol{g}(\boldsymbol{q})=\boldsymbol{\tau} \tag{1}$$

where $\boldsymbol{q}\in\mathbb{R}^n$ is the vector of joint variables, $\boldsymbol{M}(\boldsymbol{q})>0$ is the mass matrix, $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}$ accounts for the Coriolis and centrifugal forces, $\boldsymbol{g}(\boldsymbol{q})$ is the influence of the gravity on the manipulator, and $\boldsymbol{\tau}\in\mathbb{R}^n$ is the control input vector.

The system is subject to non-convex constraints. Here we consider three classes of constraints:

- *Input Saturation:* the torque applied to the joints is limited, i.e. $\boldsymbol{\tau}_{min}\leq\boldsymbol{\tau}\leq\boldsymbol{\tau}_{max}$, with $\boldsymbol{\tau}_{min}<0$ and $\boldsymbol{\tau}_{max}>0$.
- *Operating Region Constraints:* the robot arm has saturated ranges and can move in a simply connected region, i.e. $\boldsymbol{Q}=\{\boldsymbol{q}:\boldsymbol{q}_{min}\leq\boldsymbol{q}\leq\boldsymbol{q}_{max}\}$.
- *Static Obstacle Avoidance:* the robot should avoid a collection of static spherical objects $j=\{1,\dots,n_0\}$ of radius r_j centered in $\boldsymbol{c}_j\in\mathbb{R}^3$. Therefore we will model the manipulator as n segments $\overline{\boldsymbol{x}_i\boldsymbol{x}_{i+1}}$, $i=\{1,\dots,n\}$.

Given the joint space dynamic model (1) and the proposed constraints, the objective is to design a computationally simple control scheme for a manipulator that has to reach the end-effector reference position $\boldsymbol{x}_{e,r}$, while satisfying the above mentioned constraints.

The control architecture consists of two layers as shown in Fig. 1. The control layer pre-stabilizes the system, whereas the navigation layer manipulates the reference of the pre-stabilized system so that the constraints are always satisfied and the robotic arm is able to track the desired reference.

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[1] Authors are with the Robotics and Multibody Mechanics Research Group, Vrije Universiteit Brussel, Core Lab Flanders Make, Brussel, Belgium. https://www.brubotics.eu/research/renmm kelly.merckaert@vub.be

[2] Marco M. Nicotra is with the Electrical, Computer, and Energy Engineering department at the University of Colorado Boulder, Boulder, CO 80309, USA. https://www.colorado.edu/faculty/nicotra/

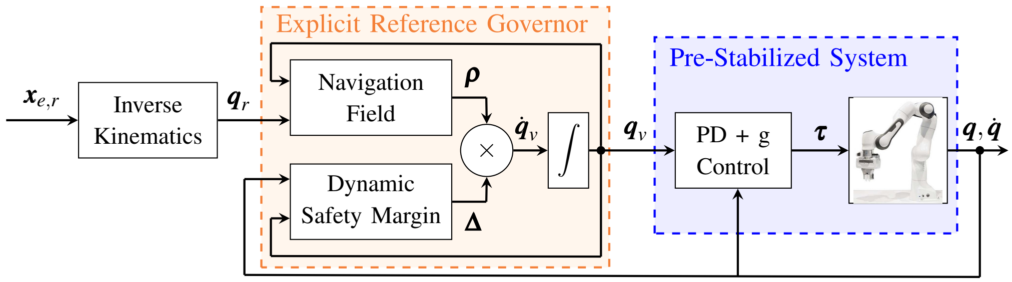

Fig. 1. Proposed Constrained Control Architecture – The desired end-effector pose $\boldsymbol{x}_{e,r}$ is given as input to the inverse kinematics block, which generates the desired joint angles $\boldsymbol{q}_r$. These desired joint angles are given to the ERG block, which returns the attainable joint angles $\boldsymbol{q}_v$ considering the imposed constraints, i.e. (3). This vector $\boldsymbol{q}_v$ is given as input reference to the PD+g control block which pre-stabilizes the manipulator, i.e. (2).

Given an auxiliary reference $\boldsymbol{q}_v$ expressed in joint space, the robotic manipulator is pre-stabilized using the classic PD with gravity compensation approach, i.e.

$$\boldsymbol{\tau} = \boldsymbol{K}_P(\boldsymbol{q}_v - \boldsymbol{q}) - \boldsymbol{K}_D\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}). \tag{2}$$

In the navigation layer, the desired reference $\boldsymbol{q}_r$ is dynamically filtered by the ERG to ensure constraint satisfaction. The idea behind the ERG is to generate the applied reference signal $\boldsymbol{q}_v$ so that, if $\boldsymbol{q}_v$ were to be frozen at any time instant, the transient dynamics of the pre-stabilized system would not violate the constraints. This is achieved by manipulating the derivative of the applied reference $\dot{\boldsymbol{q}}_v$ in continuous time using the nonlinear control law

$$\dot{\boldsymbol{q}}_v = \boldsymbol{\rho}(\boldsymbol{q}_v, \boldsymbol{q}_r)\,\Delta(\boldsymbol{q}, \dot{\boldsymbol{q}}, \boldsymbol{q}_v)\,, \tag{3}$$

where $\boldsymbol{\rho}(\boldsymbol{q}_v, \boldsymbol{q}_r)$ is the *navigation field*, i.e. a vector field that generates a constraint-admissible path of equilibria that connects the applied reference $\boldsymbol{q}_v$ with the desired reference $\boldsymbol{q}_r$ requested by the user, and $\Delta(\boldsymbol{q}, \dot{\boldsymbol{q}}, \boldsymbol{q}_v)$ is the *dynamic safety margin*, i.e. a measure of the distance between the constraints and the future trajectory of the system if $\boldsymbol{q}_v$ were to remain constant. In the Trajectory-Based ERG, the forward dynamics are simulated by using the Simplectic Euler for a finite time horizon with initializations $\hat{\boldsymbol{q}}(0) = \boldsymbol{q}$ and $\dot{\hat{\boldsymbol{q}}}(0) = \dot{\boldsymbol{q}}$.

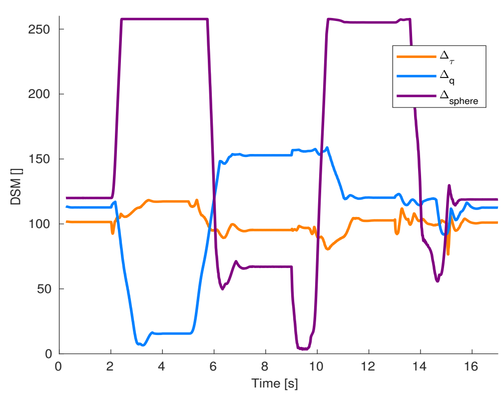

Fig. 2. Dynamic Safety Margin (DSM) of the torques (Δ_τ), joint angles (Δ_q), and spherical obstacle (Δ_{sphere}) for an experiment where step references are given to the robotic manipulator.

We validated this methodology on the Franka Panda robotic manipulator during a pick-and-place task. In Fig. 2 we can see that the end-effector reference given in $t \in [2,5]$ s was very close to one of the joint angle limits since Δ_q is pushed towards 0. The end-effector reference given in $t \in [5,10]$ s was in the interior of the spherical obstacle, but the robot could avoid it and go back to its initial configuration. The robot was slowed down by the respective DSM values as can be seen in Fig. 2.

In the accompanying video, i.e. `https://youtu.be/VAYV9x25da4`, we show experiments with wall and cylindrical obstacles in which the robot has to carry a load of 2 kg. The more weight is added to the robot end-effector, the more important the torque constraints become.

III. Conclusions

The proposed real-time control scheme can successfully satisfy input and state constraints while steering the robotic manipulator towards the desired end-effector positions or an admissible approximation thereof. The experiments are presented for static environments, but the proposed methodology is still usable in real-time for dynamic environments with model and environmental disturbances, which will be part of our future work.

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