Compliant Explicit Reference Governor for Contact

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I. Introduction

As robots take on increasingly complex tasks in dynamic environments, the conventional paradigm of strictly "collision-free" motion planning becomes limiting. Yet in critical domains such as assisted living, surgical, space robotics, and nuclear environments, contact is often essential. Robots must push, clear, and interact with their surroundings to complete the task at hand. In such contexts, avoiding contact is not just limiting—it undermines the feasibility of autonomous operation. Although allowing contact can improve efficiency, it raises concerns about safety.

Existing methods for robot-environment interaction include traditional force/position and impedance controllers [17, 6], which offer simplicity but lack inherent constraint handling. Optimization-based approaches [8, 9, 16] address constraints more directly but often rely on solving complex LCPs within Model Predictive Control, making them computationally expensive. Reinforcement learning methods [10, 1, 2, 18, 3] provide high-level planning capabilities, but typically require a separate low-level controller to enforce safety. Methods like anticipating contact to dynamically reduce contact forces ensure safe contact, [4], however, proposed scheme avoids contact, rather than leveraging it.

To reduce complexity, hierarchical strategies incorporate an intermediate safety layer that enforces constraints at the low level. These include energy-based methods [14] and control barrier functions [11]. We explore an alternative approach: manipulating the controller's reference rather than its compliance. This is achieved using an Explicit Reference Governor (ERG), a safety filter with formal guarantees for constraint satisfaction and stability [15].

Previous ERG frameworks have enabled real-time constrained control for joint limits, velocity bounds, input saturation, and obstacle avoidance [12, 13]. However, they do not permit contact, even when contact is beneficial. This paper introduces the Compliant ERG (CERG), a method that enables robots to actively avoid contact during free motion and safely regulate energy during contact. The approach transitions between these modes automatically and can be integrated with any existing controller, transforming it into a compliant controller without the need for specialized architectures. By enabling deliberate and safe contact, CERG facilitates effective motion in cluttered and contact-rich environments.

II. Problem Statement and Preliminaries

We consider the dynamic model of a fully actuated robotic arm governed by the Euler-Lagrange equation [12], Eq. (1), with joint positions, velocities and input torque $q, \dot{q}, u \in \mathbb{R}^n$, and full state $x = [q; \dot{q}]$. The system is subject to hard constraints $h(q, \dot{q}, u) \leq 0$, representing joint limits, velocity limits, actuator saturation, and forbidden contact surfaces, as well as a soft constraint $s(q) \leq 0$, representing a surface that may be contacted with limited energy. The arm is in free motion when $s(q) < 0$ and in contact when $s(q) \geq 0$. We design a constrained control strategy that leverages compliance to smoothly transition between free motion and contact. The controller must:

- Enforce $h(q, \dot{q}, u) \leq 0$ at all times;
- Enforce $s(q) < 0$ or ensure safe contact;
- Track a reference $r \in \mathbb{R}^n$, when feasible;
- Operate in real time with limited computational resources.

Given a goal r, ERG constructs an auxiliary reference v that approaches r while ensuring constraint satisfaction. Two components define the ERG framework. First, the **Navigation Field** answers the kinematic question: *what admissible steady-state path can the robot follow to reach the reference?* Second, the **Dynamic Safety Margin** answers the dynamic question: *how fast can the robot move along this path without violating constraints?* For formal definitions, proofs of safety and stability, see [15].

We build on previous work that applied ERG [12, 13] to enforce hard constraints of the form $h(q, \dot{q}, u) \leq 0$, and extend the framework to explicitly incorporate soft constraints, thus enabling safe contact.

III. Compliant Explicit Reference Governor

The objective of the Compliant ERG is to manipulate the auxiliary reference derivative, $\dot{v}(t) = \Delta(x, v)\rho(v, r)$, such that:

- *During Free Motion:* Total energy remains unconstrained to avoid speed reduction due to kinetic energy limits.
- *During Contact Operations:* Total system energy $V(x(t), v(t))$ must remain below a safety threshold, defined as maximum energy of interaction, $E_{\max} > 0$.

These conditions are compactly expressed as the logic OR ($\vee$) constraint

$$s(q(t)) < 0 \vee V(x(t), v(t)) \leq E_{\max}, \quad \forall t \geq 0, \tag{1}$$

which is equivalent to [7]

$$\min(s(q), V(x, v) - E_{\max}) \leq 0. \tag{2}$$

To also handle hard constraints $h(q, \dot{q}, u) \leq 0$, we define the constraint set

$$c(x, u, v) = [h(q, \dot{q}, u); \min(s(q), V(x, v) - E_{\max})], \tag{3}$$

$c(x(t), u(t), v(t)) \leq 0$ must be satisfied for all $t \geq 0$.

The compliant ERG can now be obtained by designing a suitable Dynamic Safety Margin and Navigation Field.

A. Compliant Dynamic Safety Margin

Inspired by the Dynamic Safety Margin (DSM) for hard constraints $\Delta_h(x, v)$ in [15], we define an analogous quantity for soft constraints, denoted $\Delta_s(x, v)$. Similar to $\Delta_h(x, v)$, $\Delta_s(x, v)$ quantifies how safe it is to manipulate $\dot{v}$ by calculating the worst soft constraint violation at any point in the future, *if the reference v were to remain constant*. Let $\Delta_h(x, v)$ be the DSM for hard constraints as in [15], and similarly defining the soft DSM $\Delta_s(x, v)$, we introduce

$$\Delta_E(x, v) = \kappa_E(E_{\max} - V(x, v)), \quad \kappa_E > 0, \tag{4}$$

and define the Compliant DSM as

$$\Delta(x, v) = \min\left(\Delta_h, \max(\Delta_s, \Delta_E)\right). \tag{5}$$

This integrates hard and soft constraints: Δ_h enforces hard limits, while $\max(\Delta_s, \Delta_E)$ ensures compliance with the disjunctive soft condition in Eq. (1), guaranteeing that any contact is within the energy bound.

B. Soft Navigation Field

The navigation field is a conservative vector field that guides v using an attraction term $\rho_{att}(v, r)$ and repulsion components. $\rho_{att}(v, r)$ drives v to r, while $\rho_h(v)$ repels v from hard constraint boundaries.

In contrast, the navigation field for soft constraints must allow penetration of the constraint boundary to enable compliant contact. To this end, we define a soft repulsion field as

$$\rho_s(v) = \max\left(\frac{s(v)}{\delta_s}, 0\right) \vec{\rho}_s(v), \tag{6}$$

where $\vec{\rho}_s(v)$ is a unit vector pointing into the interior of the soft constraint. The formulation is such that it ensures $\rho_s(v)$ is active only when v lies within the soft constraint. The complete navigation field combines all components:

$$\rho(v, r) = \rho_{att}(v, r) + \rho_h(v) + \rho_s(v), \tag{7}$$

and may be integrated with a Rapidly-exploring Random Tree (RRT) planner to avoid convergence to local minima.

IV. Results

We consider the 7-DoF Franka Emika Robot and simulate the force interactions using the Compliant Contact Model in DRAKE, which accounts for dissipation, stiffness, and static/dynamic friction of the constraint. For more details, refer to [19]. Videos of these examples can be found on https://yaashia-g.github.io/publications/CERG/. The robot is subject to hard constraints on end effector velocity, joint velocities, and joint limits, that are necessary for the functioning of the robot, as specified in [5]. The reference was deliberately selected to bring the arm into contact with the obstacle. The end-effector constraint is given by $p_x \leq 0.2$, while the target reference is $f(r) = [0.3,\ 0,\ 0.59]^\top$. Fig. 1 illustrates the simulation environment and the final configuration of the robot arm. Fig. 2 presents the interaction forces with the environment, comparing performance with and without the proposed C-ERG scheme. As expected, C-ERG effectively limits the forces exchanged during contact by constraining the total energy of the closed-loop system. The robot maintains energy greater than $E_{\max}$ during free motion and less than $E_{\max}$ during contact, enabling both efficient motion and safe interaction.

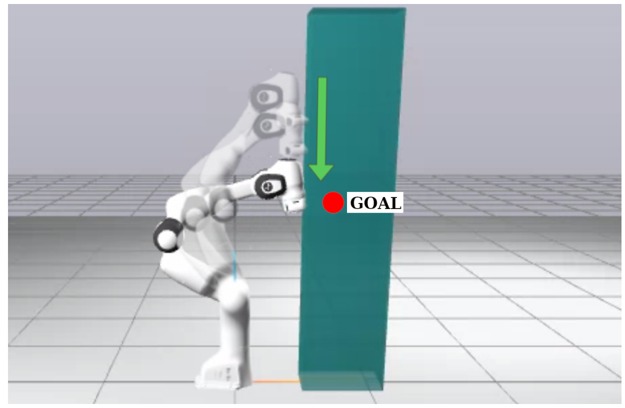

Fig. 1: The final position of the Franka Emika Arm in simulation. The C-ERG scheme enables the Franka to safely glide along the length of the soft constraint without harming either the robot or the soft constraint.

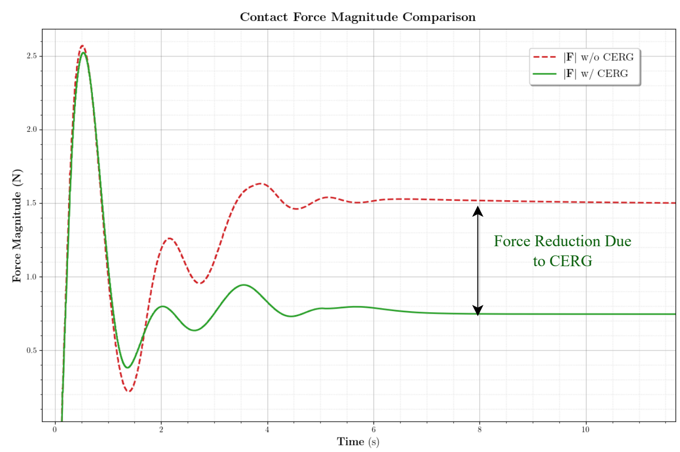

Fig. 2: The magnitude of contact force vector for the compliant point contact model with and without C-ERG. The forces without C-ERG are significantly higher as expected. This shows that CERG can limit Forces of interaction.

V. Conclusions and Limitations

This paper introduced the Compliant ERG, a safety filter that modifies a robot arm's reference to ensure constraint satisfaction. Its key contribution is enabling seamless transitions between *free motion*, with unrestricted energy, and *contact*, with limited energy. Simulations validate the method on a realistic robotic arm. Future work will explore integration with task-level planners and deployment to more specific tasks.

Limitations: The current CERG formulation does not explicitly model the object dynamics during contact, relying only on a compliant contact model. Additionally, whole-body contact and multi-contact scenarios are not yet addressed within this framework an dcan be included in future versions.

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