Errata for "Tactile-based Blind Grasping: A Discrete-Time Object Manipulation Controller for Robotic Hands"

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***Abstract*—The manuscript "Tactile-based Blind Grasping: A Discrete-Time Object Manipulation Controller for Robotic Hands" contains results that are dependent on two references. Since publication, we realized that one of these references has questionable results regarding continuity of quadratic programs. The second reference has updated conditions that are not completely reflected in the original manuscript. We take the time here to replace the questionable reference and update this manuscript to preserve the theoretical guarantees of the proposed controller. We note that this correction does not change the proposed control law, and is made to formally ensure that the guarantees hold.**

I. Proof of Theorem 1

The proof of Theorem 1 requires results from [1] on the continuity of quadratic programs. However, since publication, we realized that the results from [1] have been put to question in [2]. Continuity properties of quadratic programs are not trivial to prove, and depends heavily on the structure of the program. To replace the dependency on [1], we must first relax the condition that the hand Jacobian J_h is uncertain. In practice, this fits well with the notion of tactile-based blind grasping as the contact locations $\boldsymbol{p}_{fc}$ are components of J_h that are provided by the tactile sensors alone. Furthermore, components of J_h are only dependent on the lengths of the links that comprise the robotic fingers. These parameters are easily measurable from the design of the hand, unlike dynamic properties such as mass and inertia that are significantly more challenging to determine. Thus in this errata we replace all instances of $\hat{J}_h$ with J_h in the manuscript.

Second, the original manuscript references [3], which has been updated to [4]. The conditions presented in [4] are slightly altered and this must be reflected in the proofs of Theorem 1 and 2.

Next, we use the results from Theorem 2.1 of [5] to ensure continuous differentiability of quadratic programs (under appropriate conditions) and update the proof of Theorem 1:

Proof. The semi-global asymptotic stability of (2), (3) with control (8), (9) follows from [4], which satisfies the dissipativity property of [6]. The one-step weak consistency property from [6] is guaranteed due to the use of the Euler approximate model in (12) and the fact that the Moore-Penrose inverse can be represented as a quadratic program with equality constraints. Since $\hat{G}$, R_{pc}, and P^T, are full row rank and smooth respect to their parameters, it follows that the quadratic program resulting from the Moore-Penrose inverse satisfies the conditions (i)-(iv) of Theorem 2.1 from [5]. Thus the solution of this quadratic program is continuously differentiable, which satisfies the Lipschitz continuity condition from [6]. Thus the proof follows directly from Theorem 3.1 of [6]. □

II. Proof of Theorem 2

To replace the dependency of [1] in the proof of Theorem 2, we must first show that the proposed control can be re-written in an equivalent format. To do so, first we re-write the original control law (19) in the continuous form:

$$\boldsymbol{u} = J_h^T R_{pc} \boldsymbol{z}^* + \hat{\boldsymbol{g}} \tag{1}$$

$$\begin{aligned} \boldsymbol{z}^* = \underset{\boldsymbol{z}}{\operatorname{argmin}} \ & \boldsymbol{z}^T Q \boldsymbol{z} \\ \text{s.t.} \quad & P^T \hat{G} R_{pc} \boldsymbol{z} = \boldsymbol{u}_m \\ & \Lambda(\tilde{\mu}') \boldsymbol{z} > \varepsilon \mathbf{1} \\ & \boldsymbol{\tau}_{min} < J_h^T R_{pc} \boldsymbol{z} + \hat{\boldsymbol{g}} < \boldsymbol{\tau}_{max} \end{aligned} \tag{2}$$

Note here we replace the original use of $\succ$ with $>$, which indicates an element-wise inequality. Also, the term $\mathbf{1}$ is a vector of appropriate size with each element equal to 1.

Now we introduce a change of variables in $\boldsymbol{z}^*$ via: $\boldsymbol{z} = R_{pc}^T \boldsymbol{z}_m + R_{pc}^T \boldsymbol{z}_f$, where $\boldsymbol{z}_m := (P^T \hat{G})^\dagger \boldsymbol{u}_m$ and $\boldsymbol{z}_f \in \mathbb{R}^{3n}$ represents the internal force component of $\boldsymbol{z}^*$. Substitution of $\boldsymbol{z}^*$ into the quadratic program yields the following equivalent quadratic program:

$$\boldsymbol{u} = J_h^T ((P^T \hat{G})^\dagger \boldsymbol{u}_m + \boldsymbol{z}_f^*) + \hat{\boldsymbol{g}} \tag{3}$$

$$\begin{aligned} \boldsymbol{z}_f^* = \underset{\boldsymbol{z}_f}{\operatorname{argmin}} \ & \boldsymbol{z}_f^T R_{pc} Q R_{pc}^T \boldsymbol{z}_f \\ \text{s.t.} \quad & \hat{G} \boldsymbol{z}_f = 0 \\ & \Lambda(\tilde{\mu}') R_{pc}^T \boldsymbol{z}_f > \varepsilon \mathbf{1} - \Lambda(\tilde{\mu}') R_{pc}^T (P^T \hat{G})^\dagger \boldsymbol{u}_m \\ & \boldsymbol{\tau}_{min} < J_h^T ((P^T \hat{G})^\dagger \boldsymbol{u}_m + \boldsymbol{z}_f) + \hat{\boldsymbol{g}} < \boldsymbol{\tau}_{max} \end{aligned} \tag{4}$$

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Note that (4) contains constraints that are linear with respect to the decision variable $\boldsymbol{z}_f$ and thus is still a quadratic program.

Now we are ready to update the second half of the proof of Theorem 2:

Proof. To apply similar stability results from Theorem 1, we need to show that the results from [4] apply to the proposed control (19). To do so, we note that (3) is the equivalent form of the proposed control written as the controller from [4]. Furthermore, the Moore-Penrose component of (3) is continuously differentiable by the same analysis in Theorem 1. Now we need to address the components $\boldsymbol{z}_f^*$ so that the results from [4] follow. To do so, we note the closed-loop dynamics of [4] require multiplication of $J_a^{-T}GJ_h^{-T}$ to the control $J_h^T((P^T\hat{G})^\dagger \boldsymbol{u}_m + \boldsymbol{u}_f) + \hat{\boldsymbol{g}}$ (we refer the reader to [4] for definition of J_a). We carry out the expression, which yields:

$$\begin{aligned} J_a^{-T}GJ_h^{-T}\boldsymbol{u} &= J_a^{-T}GJ_h^{-T}\left(J_h^T((P^T\hat{G})^\dagger \boldsymbol{u}_m + \boldsymbol{z}_f^*) + \hat{\boldsymbol{g}}\right) \\ &= J_a^{-T}G(P^T\hat{G})^\dagger \boldsymbol{u}_m + J_a^{-T}G\boldsymbol{z}_f^* + J_a^{-T}GJ_h^T\hat{\boldsymbol{g}} \end{aligned}$$

From (4) it follows that $\hat{G}\boldsymbol{z}_f^* = 0$. Now from Lemma 5 of [4] and definition of $\hat{G}$, it follows that $G\boldsymbol{z}_f^* = 0$. Thus continuous differentiability of $\boldsymbol{z}_f^*$ is not required as the effect of $\boldsymbol{z}_f^*$ does not affect the closed loop system dynamics. Thus the stability results from [4] follow for the continuous time version of the proposed control, and the sampled-data results similar to Theorem 1 also follow for the proposed control (19).

Consequently, by choosing N sufficiently large, $(\boldsymbol{e}, \dot{\boldsymbol{e}})$ will converge to a ball about the origin for $t \in (0, NT_s)$. Thus it is straightforward to show that $\ddot{\boldsymbol{q}}, \dot{\boldsymbol{q}}$ are bounded in closed loop under the proposed control as $N \to \infty$ and there exists $\varepsilon = \max\{\varepsilon_k : k > 0\}$ such that semi-global practical asymptotic stability and (5) holds. Note that the maximum sampling time, $T_s^* \in \mathbb{R}_{>0}$ of the system such that semi-global practical asymptotic stability and (5) holds is: $T_s^* = \min\{T_1^*, T_2^*\}$, where $T_2^* \in \mathbb{R}_{>0}$ is the maximum allowable sampling time from the semi-global practical stability condition. □

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