A Framework for Bimanual Folding Assembly Under Uncertainties

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I. Introduction

Assembly tasks require the manipulation of at least two objects, where contact interactions are a predominant feature. Classical examples from robotics are the peg-in-hole problem, screwing and snap-fitting, to name a few. A robotic manipulator tasked with executing an assembly task will have to adjust the relative pose of the assembly-relevant objects until a final desired state is achieved. Under minor geometric uncertainties, methods such as the addition of a remote center of compliance or active impedance control of the robot arms will prevent excessive contact forces due to attempted motion along constrained directions.

The assembly of certain products, such as small scale production items or low shelf life electronics such as cellphones, require a robotic assembly system to be deployed in a relatively unstructured environment, where uncertainties can be much more significant than in traditional robotics. For example, the deployment time of the robotic system might prevent custom engineered solutions for part detection and grasping, which will result in a reasonable ammount of uncertainty in the parts' grasp. This prevents purely force-control based solutions to succeed in the assembly execution.

In our work, we focus on a folding assembly skill [1], [2]. This is a relevant skill in some electronics assembly applications, such as cellphone assembly or battery insertion, where two parts must be "closed" (folded) into each other in order to execute the assembly step [3]. In such an application, knowledge of motion directions and contact location is crucial in order to maintain contact stability while successfully executing the desired kinematic motion.

We propose a bimanual framework to execute a folding assembly task while under uncertainties in the grasp exerted on the assembly parts, and on the contact location between the two assembly objects. Bimanual manipulation enables assembly execution without relying on external fixtures, and it is an anthropomorphic feature that facilitates human-robot cooperation [4]. The Extended Coordinate Task Space (ECTS) method [5] is leveraged to allow the regulation of how the robot arms divide the task, while adaptive estimators are used to identify the kinematic uncertainties.

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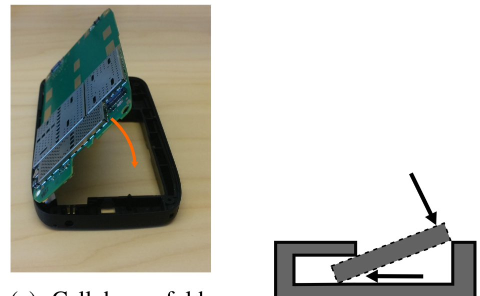

(a) Cellphone folding (b) Battery folding

Fig. 1: Examples of folding assembly tasks.

II. Definition and model of folding assembly

We define folding assembly as an assembly problem where two objects in contact are required to perform a relative rotation about some hinge point. Additionally, a relative translational motion is allowed as a condition for reaching the hinge, Fig. 1. A crucial distinction between folding and screwing can be made by imposing the condition that the rotation and translation axes must not be aligned. Furthermore, in a folding operation contact is unilateral during the complete assembly execution.

The kinematics of the folding assembly task can be written in terms of relative velocities between the assembly parts,

$$\begin{aligned} \boldsymbol{v}_s &= \mathbf{S}(\mathbf{r}_1)\boldsymbol{\omega}_{e_1} - \mathbf{S}(\mathbf{r}_2)\boldsymbol{\omega}_{e_2} - \dot{\mathbf{p}}_{e_1} + \dot{\mathbf{p}}_{e_2} \\ \boldsymbol{\omega}_r &= \boldsymbol{\omega}_{e_2} - \boldsymbol{\omega}_{e_1}, \end{aligned} \tag{1}$$

where $\boldsymbol{v}_s$ denotes a *sliding* velocity at the contact point and $\boldsymbol{\omega}_r$ corresponds to a relative angular velocity. These two quantities depend on the end-effectors linear and angular velocities, respectively $\dot{\mathbf{p}}_{e_i}$ and $\boldsymbol{\omega}_{e_i}$, with $i = \{1, \ 2\}$ indexing the robotic arm. Knowledge of the contact point $\mathbf{p}_c$ is assumed in order to define the virtual sticks $\mathbf{r}_i = \mathbf{p}_c - \mathbf{p}_{e_i}$, which connect the end-effectors to the contact location. To execute the control law, the contact point will have to be estimated, as detailed in section IV-A. Finally, given a translational direction $\mathbf{t}$ and a rotational direction $\mathbf{k}$, we assume the motion constraints

$$\begin{aligned} (\mathbf{I}_3 - \mathbf{t}\mathbf{t}^\top)\boldsymbol{v}_s &= 0 \\ (\mathbf{I}_3 - \mathbf{k}\mathbf{k}^\top)\boldsymbol{\omega}_r &= 0, \end{aligned} \tag{2}$$

that is, the sliding velocity is defined along the translational direction and the relative angular velocity is constrained to be along the rotational direction.

III. Bimanual folding assembly

The kinematics of the assembly problem are represented as a relative motion at the contact location (1). This can be translated into a relative motion of the robot end-effectors, which constitutes a relative motion twist, $\mathbf{v}_r = [\boldsymbol{v}_s^\top, \boldsymbol{\omega}_r^\top]^\top$. The ECTS framework organizes the dual-armed robot task-space in terms of absolute and relative motion twists, respectively $\mathbf{v}_a$ and $\mathbf{v}_r$, and defines an ECTS Jacobian, $\mathbf{J}_E(\alpha)$, which translates the task space motion twists into desired joint velocities for the system. The parameter $\alpha \in [0, 1]$ determines the degree to which the arms contribute to the relative motion task: in the limit, only one arm contributes to $\mathbf{v}_r$, with any intermeadiate distribution of $\mathbf{v}_r$ being allowed.

The final assembly model can be represented by

$$\mathbf{v}_E = \begin{bmatrix}\mathbf{v}_a \\ \mathbf{v}_r\end{bmatrix} = \mathbf{J}_E(\alpha)\dot{\mathbf{q}}, \quad (3)$$

with $\mathbf{q}$ denoting the dual-arm manipulator joint state. Given a task space motion twist $\mathbf{v}_E$, we can invert (3) to obtain the desired joint velocites.

IV. Control and Estimation

The target velocities for the assembly task can be directly specified by the user, or obtained through an external position control loop. For example, given a desired relative position, p_d, and orientation, θ_d, between the parts, we can generate the velocity references as

$$\begin{aligned} v_d &= \alpha_p(p_d - \mathbf{p}_c^\top \mathbf{t}) \\ \omega_d &= \alpha_\theta(\theta_d - \theta_c), \end{aligned} \quad (4)$$

where θ_c is the computed angle between the assembly parts around $\mathbf{k}$, and α_p, α_θ are respectively the position and orientation controller gains.

A. Contact point estimation

Determining the location of the contact point is a crucial step towards the manipulation control using (3). We implemented a Kalman filter to resolve this uncertainty, which combines the process model (1) with the force-torque measurement equation

$$\tau_i = \mathbf{r}_i \times \mathbf{f}_i \quad (5)$$

B. Adaptive estimation of motion directions

We exploit the motion constraints (2) to identify the motion directions and, simultaneously, generate the velocity signals used in (3), using a similar strategy to [6]. We command the sliding velocity as

$$\boldsymbol{v}_{\text{ref}} = \hat{\mathbf{t}}v_d - (\mathbf{I}_3 - \hat{\mathbf{t}}\hat{\mathbf{t}}^\top)\boldsymbol{v}_f, \quad (6)$$

and the relative angular velocity is commanded as

$$\boldsymbol{\omega}_{\text{ref}} = \hat{\mathbf{k}}\omega_d - (\mathbf{I}_3 - \hat{\mathbf{k}}\hat{\mathbf{k}}^\top)\boldsymbol{\omega}_\tau, \quad (7)$$

where the hats $\hat{\cdot}$ denote estimates and $\boldsymbol{v}_f$, $\boldsymbol{\omega}_\tau$ are respectively force and torque regulation components that ensure contact maintenance along the directions that are complementary to respectively $\hat{\mathbf{t}}$ and $\hat{\mathbf{k}}$. These regulation terms are crucial in the adaptation laws for $\hat{\mathbf{t}}$ and $\hat{\mathbf{k}}$,

$$\begin{aligned} \dot{\hat{\mathbf{t}}} &= -\gamma_t v_d(\mathbf{I}_3 - \hat{\mathbf{t}}\hat{\mathbf{t}}^\top)\boldsymbol{v}_f \\ \dot{\hat{\mathbf{k}}} &= -\gamma_k \omega_d(\mathbf{I}_3 - \hat{\mathbf{k}}\hat{\mathbf{k}}^\top)\boldsymbol{\omega}_f, \end{aligned} \quad (8)$$

where γ_t and γ_k are adaptation gains.

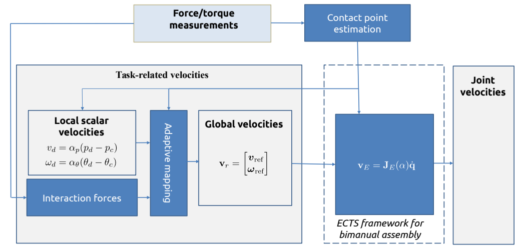

Fig. 2: Folding framework.

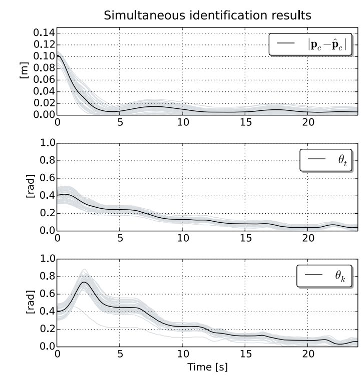

Fig. 3: Identification results for thirty consecutive experiments where the velocity references are set by the user in a feedforward fashion.

V. Assembly Architecture and Conclusions

We implemented a folding assembly architecture that follows the presented methodology. Schematically, the system is designed as in (2), and some identification results are presented in Fig. 3, where θ_t and θ_k denote, respectively, the angle between $\mathbf{t}$ and $\hat{\mathbf{t}}$ and $\mathbf{k}$ with $\hat{\mathbf{k}}$.

The framework is currently being integrated in the final SARAFun assembly system [3]. Future work will incide on how the position control loop (4) can be adapted such that contact state transitions are addressed, i.e., when the translational motion direction becomes another force control direction due to changes in the contact state.

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