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DYNAMIC MODELING OF A MULTI-CHANNAEL VACUUM GRIPPER SYSTEM AND TRAJECTORY OPTIMIZATION FOR MANIPULATOR ROBOTS IN AUTOMATED GLASS SHEET SORTING AND TRANSFER LINES

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Abstract: Automated sorting and transfer lines for thin and large-format glass sheets require high throughput while strictly preventing surface micro-cracks, bending deflection, and vacuum loss caused by inertial loads. This study presents an integrated dynamic model of a multi-channel vacuum gripper mounted on an articulated industrial manipulator robot, coupled with a time-energy optimal trajectory planning method for glass sheet handling. The coupled system dynamics combine rigid-body manipulator kinematics and dynamics with an airflow-capacitance vacuum pressure model and thin-plate bending behavior of the gripped glass sheet. Trajectory generation is formulated as a constrained optimal control problem using quintic B-spline parameterization and sequential quadratic programming (SQP) to minimize transfer time and actuator energy while bounding peak normal acceleration, jerk, and glass deflection. Simulation results for a 6-DOF manipulator handling a 1800 times 1200 times 4 mm float glass sheet across a 1.4m transfer stroke demonstrate a 24.6% reduction in cycle time and a 31.2% reduction in mechanical energy consumption compared to a conventional trapezoidal velocity profile, while maintaining maximum glass deflection below 0.42mm and vacuum safety factor above 2.8.
Keywords: multi-channel vacuum gripper; glass sheet handling; manipulator dynamics; trajectory optimization; vacuum pressure dynamics; thin-plate bending

Introduction

In modern architectural, automotive, and display glass manufacturing, automated sorting and transfer lines replace manual handling to improve repeatability, cycle speed, and workplace safety. However, glass sheets present a challenging payload for robotic manipulators: they are brittle, prone to stress concentration around edge flaws, susceptible to out-of-plane bending under inertial acceleration, and non-permeable, which makes vacuum suction arrays the standard end-effector choice.

A **multi-channel vacuum gripper** distributes lifting force across an array of suction cups, each supplied through dedicated or manifolded pneumatic channels. While multi-channel designs increase load capacity and redundancy against partial seal leakage, rapid acceleration and deceleration generate lateral shear forces, peeling moments, and pressure fluctuations across individual channels. If trajectory profiles contain step changes in acceleration or excessive jerk, structural vibrations and transient suction drops can cause sheet slippage or fracture.

Existing literature often treats manipulator trajectory optimization and vacuum gripper sizing separately. Trajectory planning studies typically enforce geometric and torque limits without explicitly coupling suction holding margins or payload plate bending, whereas pneumatic gripper models frequently assume quasi-static loads. Addressing this gap requires a unified framework that links **manipulator dynamics**, **multi-channel vacuum pressure dynamics**, and **sheet deflection constraints** directly into trajectory optimization.

The objectives of this study are to:

1. Formulate a coupled dynamic model of a multi-channel vacuum gripper and articulated manipulator handling a flexible glass sheet under inertial loads.

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2. Derive explicit safety constraints linking suction pressure margin, shear slip resistance, and allowable glass bending deflection to manipulator motion profiles.

3. Optimize the pick-and-place trajectory using smooth spline parameterization to balance cycle time, energy efficiency, and structural safety.

Methods

2.1 Coupled Manipulator and Payload Dynamics

Consider an n-degree-of-freedom (DOF) serial manipulator carrying a multi-channel vacuum gripper attached to a rectangular glass sheet of mass m_g, length L_x, width L_y, and thickness t_g. In generalized joint coordinates $q \in R^n$, the rigid-body equations of motion are expressed as:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) = \boldsymbol{\tau} - \mathbf{J}_e(\mathbf{q})^{\mathsf{T}}\mathbf{F}_{\text{ext}}$$

where Mq is the symmetric positive-definite inertia matrix, C(q,q)q represents Coriolis and centrifugal terms, g(q) is the gravitational torque vector, T is the joint torque vector, $J_e(q)$ is the end-effector Jacobian, and $\mathbf{F}_{\text{ext}} = [\mathbf{f}_{\text{load}}^{\mathsf{T}}, \mathbf{m}_{\text{load}}^{\mathsf{T}}]^{\mathsf{T}}$ denotes the net wrench exerted by the glass sheet and gripper payload on the wrist.

Let the gripper frame {G} be located at the geometric centroid of the suction array, with unit axes x_G, y_G, z_G, where z_G points normal to the glass surface away from the suction cups. For translational acceleration p_G and angular acceleration ω_G of the glass center of mass, the inertial force $F_{inertial}$ and moment $M_{inertial}$ acting at the glass centroid are:

$$\mathbf{F}_{\text{inertial}} = m_g(\ddot{\mathbf{p}}_G - \mathbf{g}_0), \qquad \mathbf{M}_{\text{inertial}} = \mathbf{I}_g\dot{\boldsymbol{\omega}}_G + \boldsymbol{\omega}_G \times (\mathbf{I}_g\boldsymbol{\omega}_G)$$

where g_0 is the gravity vector and I_g is the inertia tensor of the glass sheet about its centroid.

2.2 Multi-Channel Vacuum Pressure and Load Distribution Model

Suppose the vacuum gripper comprises N suction cups located at positions $\mathbf{r}_i = [x_i, y_i, 0]^{\mathsf{T}}$ relative to {G}, each with effective sealing area $A_{c,i}$ and static/dynamic friction coefficient μ_i against smooth glass. Using a lumped pneumatic capacitance model for channel ï with internal volume V_i, supply/valve conductance $C_{s,i}$, ambient pressure P_{atm}, and local vacuum pressure P_i:

$$V_i\frac{dP_i}{dt} = \dot{m}_{\text{in},i}(P_{\text{atm}}, P_i, u_{\text{valve},i}) - \dot{m}_{\text{leak},i}(P_i, \delta_{\text{gap},i})$$

where $m_{in,i}$ is governed by the vacuum generator/ejector or proportional valve command $u_{valve,i}$, and $m_{leak,i}$ accounts for micro-leakage across the lip seal (including minor edge or surface irregularities $\delta_{gap,i}$).

The normal suction force provided by cup i is $F_{n,i} = A_{c,i}(P_{\text{atm}} - P_i)$. Decomposing the net load at the gripper frame into normal force $F_{z,req}$ along z_G, shear force $F_{xy,req} = [F_{x,req}, F_{y,req}]^T$ in the glass plane, and overturning/peeling moment $M_{xy,req} = [M_{x,req}, M_{y,req}]^T$, a simplified quasi-static load-sharing model distributes normal retention demand across the N cups:

$$F_{n,i,\text{req}} = \frac{F_{z,\text{req}}}{N} + \frac{M_{y,\text{req}}\,x_i}{\sum_{k=1}^{N} x_k^2} - \frac{M_{x,\text{req}}\,y_i}{\sum_{k=1}^{N} y_k^2}$$

To prevent sliding and suction detachment across all channels, two operational constraints are enforced at every instant:

1. **Shear slip margin:** $\sqrt{F_{x,\text{req}}^2 + F_{y,\text{req}}^2} \leq \frac{1}{S_f} \sum_{i=1}^{N} \mu_i F_{n,i}$, where $S_f > 1$ is the safety factor against lateral slip.

2. **Normal pull-off margin:** $F_{n,i} \geq S_f \max(F_{n,i,\text{req}}, 0)$ for all $i = 1, \ldots, N$.

2.3 Glass Bending Deflection Approximation

During vertical acceleration or tilted transfer, inertial and gravitational loads distributed over the unsupported span of the glass sheet induce bending deflection w_{max}. Modeling the sheet locally as a rectangular plate with effective span L_{eff} between outer suction supports and flexural rigidity $D = \frac{E_g t_g^3}{12(1-\nu_g^2)}$ (with Young's modulus E_g and Poisson's ratio ν_g), maximum deflection scales as:

$$w_{\max}(t) \approx \alpha_b \frac{q_{\text{eff}}(t)\, L_{\text{eff}}^4}{D}$$

where α_b is a boundary-condition coefficient and $q_{eff}(t)$ is the net distributed pressure load normal to the sheet surface. Keeping $w_{max}(t) < w_{allow}$ limits bending tensile stress well below the allowable design strength of annealed or tempered float glass.

2.4 Trajectory Optimization Formulation

Between pick-up pose x_{start} at t = 0 and place-down pose x_{goal} at total transfer time T, the Cartesian or joint-space trajectory s(t) is represented using fifth-order (quintic) B-splines to guarantee C^2 continuity (smooth position, velocity, and acceleration) and bounded jerk.

The optimal control problem selects spline control points P and total duration T to minimize a weighted objective combining cycle time and actuator energy:

$$\min_{\mathbf{P},T} \; J(\mathbf{P},T) = w_t T + w_e \int_0^T \|\mathbf{W}_\tau \boldsymbol{\tau}(t)\|_2^2 \, dt$$

subject to:

Boundary conditions: $\mathbf{s}(0) = \mathbf{s}_{\text{start}}, \mathbf{s}(T) = \mathbf{s}_{\text{goal}}$, with zero initial and terminal velocities and accelerations.

Kinematic and actuator limits: $|\dot{\mathbf{q}}(t)| \leq \dot{\mathbf{q}}_{\max}$, $|\ddot{\mathbf{q}}(t)| \leq \ddot{\mathbf{q}}_{\max}$, $|\dddot{\mathbf{q}}(t)| \leq \dddot{\mathbf{q}}_{\max}$, and $|\boldsymbol{\tau}(t)| \leq \boldsymbol{\tau}_{\max}$.

Vacuum and structural limits: $F_{n,i}(t) \geq S_f F_{n,i,\text{req}}(t)$, shear slip margin $\geq S_f$, and $w_{\max}(t) \leq w_{\text{allow}}$.

Results

A numerical simulation study was conducted in a coupled rigid-body and pneumatic dynamics environment for a 6-DOF industrial manipulator transferring a 1800 X 1200 X 4mm soda-lime float glass sheet (m_g = 21.6 kg, ρ_g = 2500 kg/m^3, E_g = 72GPa, ν_g = 0.22) along a 1.4m horizontal and vertical sorting stroke using an 8-cup (2 X 4 array) vacuum gripper operating at 65kPa gauge vacuum (S_f = 2.5, w_{allow} = 1.5mm).

The **optimized quintic B-spline trajectory** was benchmarked against a **conventional trapezoidal velocity profile** constrained to the same nominal peak joint torque and vacuum safety limits.

Performance Metric	Trapezoidal Profile (Baseline)	Optimized Quintic B-Spline	Relative Improvement
Transfer Cycle Time (T)	2.28 s	1.72s	**-24.6\%** (faster)
Mechanical Energy Index ($\int \|\|\tau\|\|_2^2 \, dt$)	148.4 $N^2 \cdot m^2 \cdot s$	102.1 $N^2 \cdot m^2 \cdot s$	**-31.2\%** (lower)
Peak Normal Acceleration	6.85m/s^2	5.10m/s^2	**-25.5\%** (smoother)
Peak Glass Deflection ($w_{\max}$)	0.79mm	0.42mm	**-46.8\%** (safer)
Minimum Vacuum Safety Factor	2.52	2.84	**+12.7\%** (higher margin)

Key behavioral findings from the simulation include:

- **Elimination of jerk spikes:** The trapezoidal profile produced step transitions in acceleration at segment boundaries, exciting structural oscillations and causing transient pressure dips in outer suction cups during deceleration. The quintic B-spline profile kept jerk bounded and continuous, smoothing the pressure response across all eight channels.
- **Asymmetric load sharing during tilting:** When the glass sheet was tilted by 15^0 near the sorting rack, gravitational and angular inertial moments increased normal pull-off demand on the lower-edge cups. Because the optimizer penalized peak load imbalance, the resulting trajectory moderated angular acceleration during the tilt phase while accelerating straight linear segments.
- **Deflection margin:** Maximum sheet bending remained at 0.42 mm (28% of the 1.5 mm allowable limit), reducing edge stress concentration during high-speed transfer.

Discussion

The results confirm that co-designing trajectory optimization with multi-channel vacuum dynamics and payload bending constraints resolves a common trade-off in glass sorting lines: shortening cycle time without sacrificing handling safety. In conventional velocity profiles, operators often detune overall speed when handling large or thin glass sheets to avoid suction loss or micro-cracking, leading to unnecessarily long takt times. By explicitly encoding vacuum retention margins and deflection limits into the optimization constraints, the manipulator operates closer to its true physical envelope only where load distribution allows.

Compared with standard point-to-point or trapezoidal planning, C^2-continuous quintic B-splines offer practical advantages for industrial controllers: they generate smooth reference positions, velocities, and accelerations without high-frequency excitation of harmonic drives or vacuum manifolds. Furthermore, accounting for non-uniform cup loading highlights why cup placement and vacuum channel monitoring matter just as much as peak vacuum level an outer cup experiencing partial leakage under high tilting moment can initiate peeling even when average manifold pressure appears adequate.

Limitations and Future Work

This study relies on numerical simulation and a quasi-static load-sharing approximation across suction cups combined with an analytical plate-bending estimate. Several limitations should be addressed in subsequent research:

1. **Experimental validation:** Hardware-in-the-loop and physical test-bench trials with high-speed pressure transducers, laser displacement sensors, and a real glass sheet are needed to calibrate leakage and damping parameters.
2. **Dynamic cup-surface contact & micro-slip:** Partial elastomer deformation and stick-slip transition at the glass–cup interface under dynamic vibration warrant detailed finite-element or contact-mechanics modeling.
3. **Fault-tolerant channel reconfiguration:** Future work should integrate real-time fault detection such as an isolated vacuum drop in one channel to trigger online trajectory deceleration or abort/re-grip routines.

Conclusion

This paper presented a coupled modeling and trajectory optimization framework for a manipulator robot equipped with a multi-channel vacuum gripper in automated glass sheet sorting and transfer lines. By linking rigid-body manipulator dynamics, multi-channel vacuum pressure and load-sharing relations, and glass bending deflection constraints within a quintic B-spline optimization formulation, the approach reduced transfer time by 24.6% and mechanical energy consumption by 31.2% in simulation while cutting maximum glass deflection by 46.8% and maintaining a vacuum safety factor of 2.84. Integrating vacuum retention and structural deflection directly into motion planning provides a practical path toward faster, safer, and more energy-efficient automated glass handling.

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