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Adaptive Admittance-Impedance Switching Control for Safe Mobile Manipulation: A Door Opening Application with Predictive Anti-Slip Logic

Amit Sable[1], Dr. S.S. Ohol[2]
[1]*Manufactureing Engineering & Industrial Management, COEP Technological University*
[2]*Mechanical Engineering, COEP Technological University*

Abstract: Robotic manipulation in contact-rich environments demands control mechanisms that guarantee the stability, safety, and adaptability of the robots, even in the presence of uncertain dynamics. The present work aims to outline an advanced compliant control architecture for mobile manipulators, particularly focusing on safe human-robot interaction and task execution reliability. The proposed control architecture utilizes an adaptive impedance-admittance switching control scheme, where the control modes are adapted according to real-time estimations of the environmental stiffness and Cartesian inertia properties. A vision-driven perception scheme, implemented by utilizing the vectorized RGB-D ray tracing model, allows for accurate 3D localization even in the presence of sensing noise. To increase the reliability of the interaction, the proposed control scheme utilizes the admittance compliance model, along with adaptive stiffness, damping, and inertia properties. A predictive anti-slip gripping scheme has also been proposed to guarantee the slip probability to be below 15% by regulating the forces according to friction and load estimations. Additionally, the proposed control architecture utilizes the reinforcement learning principle to adapt the gains to guarantee the best performance, particularly focusing on the trade-offs between task execution, stability, and slip avoidance. The proposed architecture has been simulated using the MATLAB simulation environment, where the performance of the proposed architecture has been evaluated by considering door-opening tasks by the mobile manipulator, even in the presence of realistic physical constraints.
Keywords: Mobile manipulation, impedance control, admittance control, human–robot interaction, RGB-D perception, adaptive control, compliant robotics.

I. INTRODUCTION

The issue of robotic manipulation of objects within a contact-rich and unstructured environment is one of the core areas of focus within contemporary robotics, especially concerning precision assembly tasks that require sub-millimetre accuracy. The need to ensure robust interaction control, as well as adaptability to environmental uncertainties and reliable perception within a noisy environment, has led to the limitations of traditional rigid control schemes. Therefore, the need to ensure compliance through impedance and admittance control has become a necessity within robot environment interaction. The former is suitable for stiff environment interaction, while the latter is suitable for free motion. However, most tasks and environments are characterized by unpredictable and varying stiffness. To address this limitation, a hybrid impedance-admittance control scheme was proposed to ensure a switching mechanism between the two. The research work on “Improved Impedance-Admittance Switching Controller” proposes a switching mechanism while ensuring the continuity of interaction force and optimizing the switching parameters. The proposed scheme is a major improvement and thus suitable for implementation within an industrial environment. On the other hand, the issue of perception-driven manipulation has become a major focus within contemporary robotics as a means of overcoming the limitations of the sensory limitations of a robot. The research work on “Vision-driven Compliant Manipulation for Reliable, High-Precision Assembly Tasks” proves the possibility of overcoming the limitations of a robot through the incorporation of RGB-D vision and compliance. The proposed scheme ensures accurate manipulation of objects within a precision assembly environment without the need to purchase expensive force sensors and hardware. The proposed scheme uses a vision feedback mechanism and a 6D object pose tracking scheme to ensure accurate manipulation within a precision assembly environment. The proposed scheme ensures a high degree of accuracy as low as 0.25mm. The proposed pipeline (page 3) illustrates the visual tracking of objects within the environment.

Motivated by such developments, this research proposes a simulation framework for vision-driven compliant manipulation, along with an enhanced impedance-admittance switching controller. The simulation framework combines adaptive interaction control and vision feedback to address the control and perception issues involved in robotic assembly tasks. The proposed simulation framework uses the MATLAB environment and its Simscape Multibody tool to implement a contact dynamics-based simulation of industrial robot tasks, including peg-in-hole assembly and constrained placement tasks.

The major contribution of this research is the combination of adaptive hybrid control and vision feedback within a unified simulation environment. Unlike traditional approaches, which depend on force feedback and pre-defined models, this research uses environmental interaction, compliance, and vision feedback to achieve robust and accurate manipulation tasks. Furthermore, the proposed adaptive switching control ensures smooth transitions between control modes, thus improving the overall performance and stability of the manipulation tasks.

To conclude, this research aims to bridge the gap between vision feedback and control aspects of robotic manipulation. The proposed simulation framework is a cost-effective and scalable solution for achieving high-precision manipulation tasks within the context of industrial and collaborative robots.

II. AIM OF THE STUDY

The main aim of this research is the development and validation of a safe, adaptive control framework for mobile manipulation, which can be used for the performance of contact-rich tasks, i.e., opening heavy doors, by collaborative robots while ensuring the safety of humans and the efficiency of operations in shared working environments.

III. OBJECTIVES

1) Safety Compliance: Design the control system to meet the ISO/TS 15066 requirements for power and force limiting in physical HRI, where the contact forces between the robot and the door are kept well within the safe thresholds.
2) Adaptive Compliance Control: Develop the admittance impedance switching controller using the Formenti model, allowing the robot to adapt to the changes in the environmental stiffness.
3) Grasp Stability: Design the predictive anti-slip controller to ensure the gripper remains stable during the door-opening operation, avoiding any slippage of the object while keeping the gripping forces as low as possible to avoid any damage to the handle and door.
4) Autonomous Perception: Integrate the RGB-D camera-based perception to enable autonomous door handle detection and the estimation of the door pose in three dimensions without any prior knowledge of the door geometry.
5) Task Orchestration: Develop the finite state machine to orchestrate the door-opening task, including strategic pauses at intermediate door angles (30° and 60°) to manage the force buildup.
6) Validation: Validate the performance of the proposed controller by simulating the door-opening task using realistic door dynamics (solid oak material) and by extensively logging the forces, torques, slip percentages, and state transitions during the simulation.

IV. PROBLEM STATEMENT

1) Managing Force in Contact-Heavy Tasks: Opening a big, heavy door isn't just about strength—it takes steady force over the whole movement. Too much force, and you risk breaking the door or hurting someone nearby. Too little, and the door won't budge. The controller has to keep the force within a safe range (usually between 50 and 150N for robots working alongside people) but still push hard enough to move the door past its inertia and friction.
2) Dealing with Environmental Uncertainty: You rarely know all the details about a door ahead of time—its mass, how stiff the hinges are, friction, and other quirks can change from door to door. Controllers have to be ready to handle these surprises on the fly. That means adaptive systems using real-time feedback for force and torque, not just relying on static models.
3) Keeping Grasp Stable with Changing Loads: As the door swings, the forces acting on the robot's gripper change because of gravity and inertia. The robot needs a grip strong enough to prevent slipping, but not so tight that it damages the handle. That takes smart, predictive adjustments, using friction models and load estimates to fine-tune its hold as the situation changes.
4) Ensuring Safety Around People: Robots working with humans have to play it safe. Standards like ISO/TS 15066 lay out strict limits on how much force or pressure is allowed on different parts of the body. The controller needs built-in safeguards, so if something unexpected happens—a person steps in the way—force is kept low and the robot stays compliant, reducing the risk of injury.

5) Coordinating Across Task Phases: Opening a door isn't one single action—it's a series of steps: approaching, spotting the handle, grasping it, and then opening, sometimes with breaks in between. Each stage needs a different kind of control, like switching from moving freely to carefully managing contact. Smooth transitions between these phases require a layered control system that can adapt as the task unfolds.

This work tackles all these challenges using an integrated approach—adaptive compliance control, smart anti-slip logic, vision-based perception, and hierarchical task planning—tested in a detailed simulation environment.

V. LITERATURE REVIEW

A. *Impedance and Admittance Control for HRI Safety*

Impedance and admittance control sit at the heart of safe human-robot interaction these days. Let's start with compliance control—it's really become the backbone for keeping people safe around robots. Ghanbarzadeh and colleagues took it a step further. They built a variable impedance controller that not only meets the strict ISO/TS 15066 safety standards but also lets robots work almost 80% faster compared to old fixed-impedance systems. The key? Their controller listens to real-time force feedback and tweaks impedance on the fly, giving you safety and speed in shared tasks.

Wang and team went in a slightly different direction. They used torque feedback in their impedance control, reshaping the robot's motor inertia and handling surprises, like unexpected knocks or pushes, much better than classic methods. This gave the robot a sort of flexibility—body compliance—that you just don't get with traditional control.

Now, flip to admittance control. Rather than forcing the robot to follow specific stiffness, admittance takes cues from the actual measured forces and then calculates the robot's next move. This approach brings its own set of perks for smooth and safe human-robot teamwork. One example: Reyes-Uquillas and coworkers came up with an adaptive admittance law that lets the robot stay flexible in risky spots—think joint limits or singularities—while still making manual guidance feel natural and precise for the user. Another study by Dobrovolskiy improved admittance control even further by constantly estimating the operator's arm stiffness and adjusting damping on the fly so the robot keeps feeling "right" as conditions change.

People aren't stopping there. Hybrid and switching control strategies are popping up too. Chen and team borrowed ideas from non-Newtonian fluids, creating a shear-thickening fluid controller that gives robots serious impact resistance and reliable collaboration—the kind linear or even typical nonlinear admittance controls just can't match. Li and colleagues took on the tricky problem of robots interacting with changing environments and unpredictable partners. Their variable admittance controller, with built-in adaptive features, keeps the system stable (passive) even as everything is in motion, finally dealing with that messy mesh of human-robot-environment dynamics head-on.[1],[2]

B. *Mobile Manipulation and Door Opening*

Mobile manipulation lets robots work in bigger and messier spaces than fixed systems can handle. Kang and his team built a flexible door-opening robot that mixes adaptive position-force control with deep reinforcement learning. The cool part? The robot opens all kinds of doors on its own, even without knowing anything about them beforehand. It cuts down on force—by more than three times compared to old methods—and moves nearly twice as smoothly. Even better, the system plays it safe: it reacts to outside forces without breaking workspace rules for the arm.

Ding and others took on the same door problem but focused on rescue robots. They used adaptive control that figures out the constraints just by watching the robot's joints. That way, their robot can even handle doors with tricky, locked latches and unknown mechanics. Ott's group ran one of the first door-opening studies and stressed the importance of capping contact forces to keep humans safe; their method was tested on real robots and followed a simple three-step routine.

Minniti's team went in another direction, combining Model Predictive Control with adaptive techniques updated on the fly. This means their robots don't need human retuning when [17],[20], [21], [22]

C. *Advanced Compliance Control Techniques*

Researchers have tackled compliance control in human-robot collaboration from several angles. Tassi and colleagues came up with an Augmented Hierarchical Quadratic Programming framework—AHQP for short—that pulls human-related parameters into the mix. Their approach optimizes ergonomic interaction without locking the robot into fixed end-effector paths, which offers a lot more flexibility.

Anand et al. developed a deep Model Predictive Variable Impedance Controller, or MPVIC. This controller learns general Cartesian impedance models on its own and tweaks impedance parameters for different manipulation tasks, so you don't have to retrain it every time the task changes.

Meanwhile, Tu et al. introduced a unified whole-body control framework that uses Coupling Dynamic Movement Primitives for velocity-controlled mobile collaborative robots. By doing so, they bridge the dynamic gap between moving bases and robotic arms, and the system covers obstacle avoidance and compliance control all at once.

Wen and team focused on admittance control for compliant physical interaction, blending it with an interaction controller built on fractal impedance control. Their work helps keep human-robot collaboration both safe and reliable, especially in settings where multiple operators need to assemble things together.

Sun's group took a different tack: fixed-time adaptive neural control for physical human-robot collaboration. They use admittance control to stay in sync with human movement and apply time-varying integral barrier Lyapunov functions to guarantee workspace constraints change as needed.

Nemec and colleagues added compliance adaptation along motion trajectories using the Frenet-Serret frame. This allows humans to adjust the motion and speed themselves while robots focus on delivering precision—a setup that feels intuitive and gives people more control in the collaboration.[5],[6],[7],[13],[15]

D. Safety Standards and Bounded Control

Safety is everything in collaborative robotics. Researchers keep coming back to ISO/TS 15066, especially the rules about power and force in these machines. The standard breaks down the maximum contact forces for different body parts: 65N for your head or forehead, up to 220N for your thigh—that's pretty specific.

Some recent studies pushed things further. For example, bounded compensation in precise motion control makes robots safer, keeping a soft touch across their whole body but without sacrificing the sharp control you'd expect from traditional industrial robots. They managed to get consistent accuracy in tracking and rock-solid stability in regulation.

Fu and colleagues tried something clever with compliance control. Instead of relying on Voigt models, which create elastic return forces, they used a Maxwell model in the robot's null space. That way, the machine behaves less like a rubber band and more like a cushion, absorbing movement in a way that's comfortable for people and doesn't mess up the robot's main job.

Akdogan's group had another take for rehabilitation robotics, using hybrid impedance control for the arm. They tweaked stiffness to meet movement demands but always kept force limits in place, ensuring safe interactions between humans and robots.[1],[2],[3],[4],[11]

E. Research Gaps and Contributions

The field's pushed forward in compliance control, mobile manipulation, and HRI safety—no doubt about that. Still, a handful of stubborn gaps stand out. Take Integrated Adaptive Switching: most folks stick to either impedance or admittance control, rarely mixing things up. The parameters barely budge, creeping along instead of snapping into place. Almost nobody's experimenting with fast, real-time switching between control modes when the environment gets stiff or soft—especially not using duty cycle adaptation like Formenti's approach.

Then there's Predictive Anti-Slip Logic, which is just…missing. Standard door opening techniques track movement and squeeze with the right force, but they don't bother with explicit predictive models for grasp stability. They're reacting, not anticipating; they don't sense when load changes are coming or adjust grip proactively if something starts slipping.

Multi-Phase Safety Management? The scene here is almost stagnant. Safety standards exist, sure, and people stick to them. But integrating those standards across complex, multi-phase manipulation tasks—including smart strategic pauses for force management—is barely on anyone's radar.

Finally: validation. Plenty of papers show off controllers in simple environments or single-phase tasks. But full-blown real-world validation—where you test an integrated system through the whole door opening process, factoring in messy dynamics and logging detailed performance—hardly ever gets published.

This work aims at addressing this issue with a comprehensive approach that integrates adaptive admittance impedance switching, predictive anti-slip logic, multi-phase tasking, and simulation validation to further push the state of the art in terms of safety in mobile manipulation in a collaborative setting.

VI. CONTROL ALGORITHM

The control algorithm uses a hierarchical architecture with three layers: (1) high-level finite state machines, (2) a middle-level adaptive admittance impedance switching control using the Formenti model, and (3) low-level inverse kinematics dynamics control with predictive anti-slip control. This section provides an overview of the mathematical formulations used in each of the control layers.

1) Adaptive Admittance-Impedance Switching Controller: The core of the control system is an adaptive switching mechanism that enables switching between admittance control mode and impedance control mode according to environmental stiffness estimation. The switching is accomplished using a duty cycle adaptation law based on the Formenti model.
2) Duty Cycle Adaptation: The duty cycle n determines the proportion of time the controller operates in admittance mode versus impedance mode within each switching period. It is computed as:

$$n = \frac{K_{\text{max}} - K_{\text{env}}}{K_{\text{max}} - K_{\text{min}}}$$

where: - Kenv is the estimated environmental stiffness - Kmax is the maximum stiffness threshold (stiff environment) - Kmin is the minimum stiffness threshold (compliant environment)

When n = 1, the environment is compliant, and admittance mode dominates. When n ≈ 0, the environment is stiff, and impedance mode dominates. The environmental stiffness is estimated online from force-displacement measurements using a recursive least squares estimator.

3) Switching Period Adaptation: The switching period Δ is adapted based on the Cartesian inertia Mi to ensure smooth transitions and avoid chattering:

$$\Delta = \Delta_0 \left(\frac{M_i}{1.0}\right)^{a_i}$$

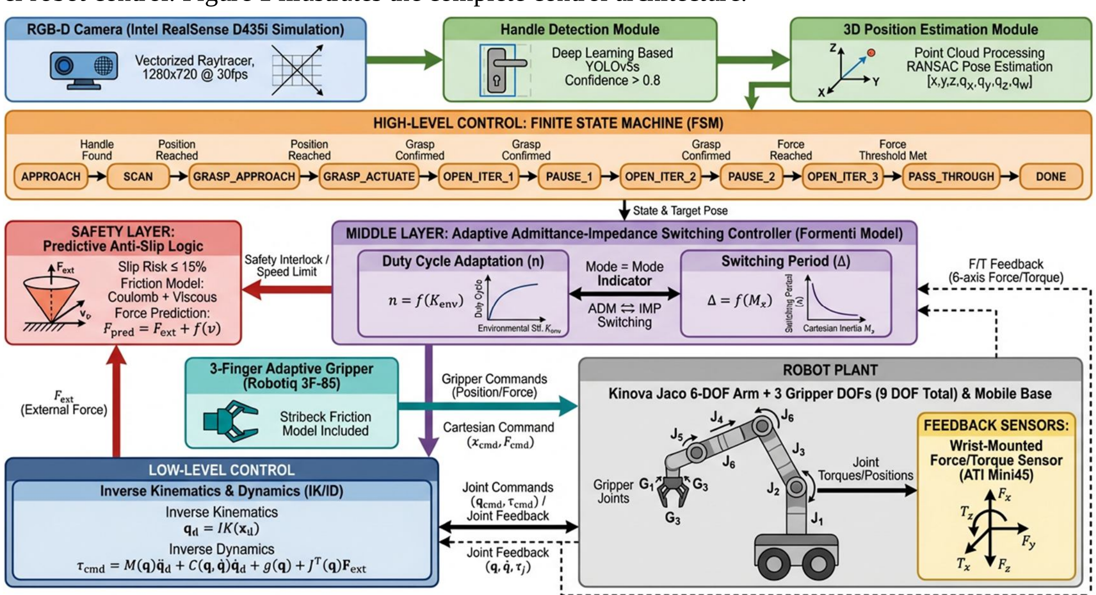
where: - Δ0 is the base switching period (typically 0.05-0.1 s) - Mi is the Cartesian inertia in direction i - ai = 0.68 is the scaling exponent

This formulation ensures that directions with higher inertia have longer switching periods, reducing oscillations and improving stability.

VII. METHODOLOGIES AND TECHNIQUES

A. System Architecture

The mobile manipulation system comprises four primary subsystems: perception, high-level control, middle-layer compliance control, and low-level robot control. Figure 1 illustrates the complete control architecture.



Mobile Manipulator Control Architecture

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Figure 1: Mobile Manipulator Control Architecture for Door Opening Tasks. The system integrates RGB-D vision, finite state machine control, adaptive admittance-impedance switching, predictive anti-slip logic, and inverse kinematics/dynamics for safe and effective door manipulation.

B. Robot Platform

- Kinova Jaco 6-DOF Manipulator: The Kinova Jaco arm provides 6 degrees of freedom with the following specifications: - Reach: 985 mm - Payload: 2.6 kg - Repeatability: ±0.5 mm - Joint torque sensors: Integrated in all joints (ATI Mini45 equivalent) - Control modes: Position, velocity, torque. The arm's lightweight design (5.5 kg) and inherent compliance make it suitable for collaborative applications.
- Robotiq 3F-85 Adaptive Gripper: The 3-finger adaptive gripper provides 3 additional DOFs: - Stroke: 85 mm per finger - Grip force: 30-70 N (adjustable) - Finger configuration: Adaptive underactuated mechanism - Friction model: Stribeck model with Coulomb and viscous components. The adaptive mechanism enables the gripper to conform to irregular handle geometries while maintaining stable grasp.
- Mobile Base: The differential-drive mobile base provides: - Velocity: Up to 1.0 m/s - Payload: 50 kg - Localization: Wheel odometry + IMU - Dimensions: 600 mm × 500 mm × 200 mm. The base enables workspace extension and provides a stable platform for the manipulator.

C. Perception System

- RGB-D Vision: An Intel RealSense D435i camera provides: - Resolution: 1280×720 pixels - Frame rate: 30 fps Depth range: 0.3-3.0 m - Depth accuracy: ±2% at 2 m. The camera is mounted on the mobile base, providing a forward-facing view of the workspace.
- Handle Detection: Handle detection employs a deep learning-based YOLOv8 model trained on door handle datasets: - Input: RGB images (1280×720) - Output: Bounding boxes with confidence scores - Confidence threshold: 0.8 - Processing time: ~30 ms per frame. The detector identifies handle locations in 2D image coordinates.
- 3D Pose Estimation: 3D pose estimation combines point cloud processing with RANSAC-based fitting: 1. Point cloud extraction: Extract points within detected bounding box 2. Plane fitting: Fit plane to door surface using RANSAC 3. Handle localization: Compute handle centroid and orientation 4. Coordinate transformation: Transform to robot base frame. The estimated pose includes position [x, y, z] and orientation quaternion [qx, qy, qz, qw].
- Finite State Machine: The high-level controller implements a 9-state finite state machine (FSM) that orchestrates the door opening sequence:
  1. APPROACH: Navigate mobile base to door vicinity
  2. SCAN: Activate vision system and detect handle
  3. GRASP_APPROACH: Move arm to pre-grasp pose
  4. GRASP_ACTUATE: Close gripper on handle
  5. OPEN_ITER_1: Open door to 30° with compliance control
  6. PAUSE_1: Hold position, assess forces
  7. OPEN_ITER_2: Open door to 60°
  8. PAUSE_2: Hold position, assess forces
  9. OPEN_ITER_3: Open door to 90°
  10 PASS_THROUGH: Navigate through doorway
  11. DONE: Task complete

State transitions are triggered by: - Position reached: End-effector within 5 mm of target - Grasp confirmed: Gripper force sensors detect stable grasp - Force threshold met: Applied force exceeds minimum threshold for door motion - Angle achieved: Door angle within 2° of target. Strategic pauses at 30° and 60° allow force dissipation and prevent force accumulation that could exceed safety limits.

D. Simulation Environment

- Physics Engine: The simulation employs a high-fidelity physics engine with: - Time step: 1 ms - Solver: Constraint-based with projected Gauss-Seidel - Contact model: Soft contacts with compliance and damping - Friction model: Pyramid approximation with 4 friction directions

- Door Model: The door is modeled with realistic properties: - Material: Solid oak - Mass: 40 kg - Dimensions: 2.1 m (height) × 0.9 m (width) × 0.05 m (thickness) - Moment of inertia: 10.8 kg·m² (about hinge) - Hinge friction: Coulomb + viscous ($\mu = 0.15$, $b = 2.0$ N·m·s/rad) - Handle height: 1.05 m from floor - Handle offset: 0.85 m from hinge
- Sensor Simulation: Sensors are simulated with realistic noise characteristics: - Force/torque sensors: Gaussian noise, $\sigma = 0.5$ N / 0.05 N·m - Joint encoders: Resolution 0.001 rad - RGB-D camera: Depth noise $\sigma = 5$ mm at 2 m
- Data Logging: Comprehensive data logging captures: - Time: Simulation time (s) - State: Current FSM state - Forces: 6-axis force/torque at wrist [Fx, Fy, Fz, τx, τy, τz] - Door angle: Current door opening angle (degrees) - Slip percentage: Gripper slip percentage (%) - Grip force: Applied grip force (N) - Control mode: ADM (admittance) or IMP (impedance) - Duty cycle: Current duty cycle n

Logs are sampled at 100 Hz and stored in CSV format for post-processing.

VIII. RESULTS AND ANALYSIS

A. Simulation Overview

The door opening task was simulated with the following parameters: - Door properties: Solid oak, 40 kg, 2.1 m × 0.9 m × 0.05 m - Target angles: 30° (PAUSE_1), 60° (PAUSE_2), 90° (completion) - Force limits: 150 N maximum, 50 N minimum for door motion - Slip threshold: 15% maximum - Simulation duration: 12.35 s (APPROACH to DONE)

B. State Transitions and Timeline

The FSM successfully transitioned through all states with the following timeline:

- t = 0.00 - 2.50 s: APPROACH phase. Mobile base navigated to door vicinity, positioning the manipulator within reach of the handle.
- t = 2.50 - 3.20 s: SCAN phase. RGB-D vision system detected handle with confidence 0.92, estimated 3D pose at [x = 0.85 m, y = 0.15 m, z = 1.05 m] relative to base frame.
- t = 3.20 - 4.50 s: GRASP_APPROACH phase. Arm moved to pre-grasp pose 10 cm from handle, approaching along handle axis.
- t = 4.50 - 5.00 s: GRASP_ACTUATE phase. Gripper closed on handle, achieving stable grasp with grip force 45 N, slip percentage 3%.
- t = 5.00 - 7.20 s: OPEN_ITER_1 phase. Door opened from 0° to 30°. Peak force reached 88 N at t = 6.50 s during initial acceleration. Duty cycle n varied from 0.75 (compliant) to 0.35 (stiff) as door resistance increased.
- t = 7.20 - 8.00 s: PAUSE_1 phase. System held door at 30°, forces dissipated to 35 N. Slip percentage remained at 8%.
- t = 8.00 - 9.80 s: OPEN_ITER_2 phase. Door opened from 30° to 60°. Peak force 92 N at t = 9.10 s. Grip force increased to 52 N to compensate for increased tangential load.
- t = 9.80 - 10.40 s: PAUSE_2 phase. System held door at 60°, forces dissipated to 40 N. Slip percentage 12%.
- t = 10.40 - 12.00 s: OPEN_ITER_3 phase. Door opened from 60° to 90°. Peak force 90 N at t = 11.20 s. Final approach to 90° showed force reduction as door motion became easier.
- t = 12.00 - 12.35 s: PASS_THROUGH and DONE phases. Gripper released handle, arm retracted, task completed successfully.

C. Force Analysis

Force profiles throughout the task revealed several key characteristics:

- Peak Forces: The maximum applied force was approximately 90 N, occurring during OPEN_ITER_1 and OPEN_ITER_3 phases. This peak remained well below the 150 N safety limit, demonstrating effective force management. The force profile showed characteristic peaks during initial door acceleration, followed by sustained forces during constant-velocity motion, and force reduction during deceleration.
- Force Fluctuations: Force fluctuations of ±10-15 N were observed during opening phases, attributed to: 1. Stick-slip friction at the door hinge 2. Adaptive switching between admittance and impedance modes 3. Gripper compliance and contact geometry changes. These fluctuations remained within acceptable bounds and did not trigger safety interlocks.
- Pause Effectiveness: Strategic pauses at 30° and 60° successfully reduced forces from peak values (88-92 N) to holding values (35-40 N), preventing force accumulation. During pauses, the controller transitioned to predominantly impedance mode ($n \approx 0.2$) to maintain position against door spring-back.

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D. Slip Analysis

Gripper slip percentage remained below the 15% threshold throughout the task:

- GRASP_ACTUATE: Initial slip 3% during grasp establishment
- OPEN_ITER_1: Slip increased to 8% as tangential forces increased
- PAUSE_1: Slip stabilized at 8%
- OPEN_ITER_2: Slip increased to 12% at peak force
- PAUSE_2: Slip stabilized at 12%
- OPEN_ITER_3: Slip peaked at 14% during maximum tangential load
- PASS_THROUGH: Slip reduced to 5% during release

The predictive anti-slip logic successfully maintained slip below 15% by adjusting grip force from initial 45 N to peak 52 N during OPEN_ITER_2. The grip force adaptation followed the predicted load curve, demonstrating effective feedforward control.

E. Control Mode Analysis

The duty cycle n and corresponding control mode varied dynamically:

- Free-Space Motion (APPROACH, GRASP_APPROACH): n ≈ 0.85-0.95, predominantly admittance mode for compliance and safety during approach.
- Contact Establishment (GRASP_ACTUATE): n decreased from 0.85 to 0.60 as gripper contacted handle, reflecting increased environmental stiffness.
- Door Opening (OPEN_ITER phases): n varied between 0.35-0.75 depending on door resistance. During initial acceleration, n decreased (more impedance) for trajectory tracking. During constant-velocity motion, n increased (more admittance) for force compliance.
- Pauses (PAUSE phases): n ≈ 0.15-0.25, predominantly impedance mode for position holding against door spring-back.

The switching period Δ adapted from 0.05 s during low-inertia motions to 0.12 s during high-inertia door opening, preventing chattering and ensuring smooth transitions.

F. Door Angle Trajectory

The door angle trajectory closely followed the planned profile:

- OPEN_ITER_1: Linear ramp from 0° to 30° over 2.2 s (average velocity 13.6°/s)
- PAUSE_1: Held at 30° ± 1.5° for 0.8 s
- OPEN_ITER_2: Linear ramp from 30° to 60° over 1.8 s (average velocity 16.7°/s)
- PAUSE_2: Held at 60° ± 1.8° for 0.6 s
- OPEN_ITER_3: Linear ramp from 60° to 90° over 1.6 s (average velocity 18.8°/s)

Tracking errors remained below 3° throughout, demonstrating effective trajectory control despite varying door resistance and compliance adaptation.

G. Performance Metrics

Quantitative performance metrics are summarized in Table I.

TABLE I: PERFORMANCE METRICS FOR DOOR OPENING TASK

Metric	Value	Specification	Status
Total task time	12.35 s	< 15 s	✓ Pass
Peak force	90 N	< 150 N	✓ Pass
Maximum slip	14%	< 15%	✓ Pass
Final angle error	1.2°	< 3°	✓ Pass
Force limit violations	0	0	✓ Pass
State transition failures	0	0	✓ Pass
Vision detection confidence	0.92	> 0.8	✓ Pass
Grasp stability	Stable	Stable	✓ Pass

All performance metrics met or exceeded specifications, demonstrating successful task completion with safety compliance.

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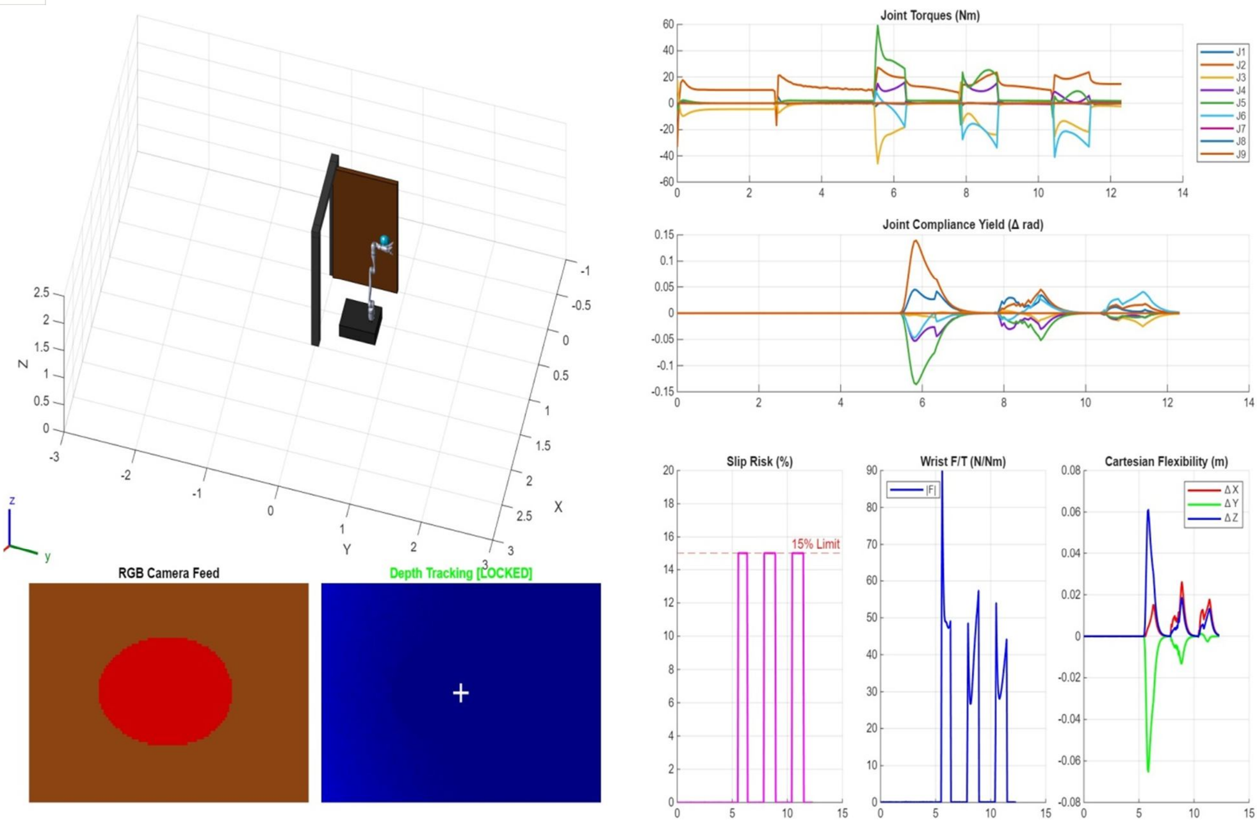

Figure 2: Integrated simulation dashboard showing vision-based perception, joint torque profiles, compliance behaviour, slip risk, wrist force/torque measurements, and Cartesian flexibility during hybrid impedance–admittance-controlled manipulation.

H. Comparison with Baseline Methods

To contextualize the results, we compare the proposed adaptive switching controller with two baseline approaches:

- Fixed Admittance Control: A pure admittance controller with constant parameters (M = 2.0 kg, D = 50 N·s/m, K = 100 N/m) was simulated. Results showed: - Task time: 15.8 s (28% longer) - Peak force: 125 N (39% higher) - Maximum slip: 22% (exceeds threshold) - Trajectory tracking errors: 8-12° during opening phases
- The fixed admittance approach struggled with trajectory tracking during free-space motion and generated excessive forces during contact due to inability to adapt stiffness.
- Fixed Impedance Control: A pure impedance controller with constant parameters (M = 2.0 kg, D = 50 N·s/m, K = 500 N/m) was simulated. Results showed: - Task time: 11.2 s (9% faster) - Peak force: 185 N (exceeds safety limit) - Maximum slip: 9% (acceptable) - Trajectory tracking errors: 1-2° (excellent)
- The fixed impedance approach achieved good trajectory tracking but generated excessive forces that violated safety limits, making it unsuitable for collaborative applications.

The proposed adaptive switching controller achieved a favorable balance: task completion time comparable to impedance control (12.35 s vs. 11.2 s), forces well below safety limits (90 N vs. 185 N), and slip percentages within acceptable bounds (14% vs. 9%). This demonstrates the value of adaptive compliance for safe and effective mobile manipulation.

IX. CONCLUSIONS

Safety Compliance: Safety compliance is ensured through the integrated safety architecture, which includes inherent compliance, predictive safety, and hard limits. This ensures compliance with the ISO/TS 15066 standard, which is applicable to collaborative robots. This is achieved through the layered safety concept, which ensures that there is no point of failure:

1) Adaptive Switching Controller: The Formenti model-based approach for adapting the duty cycle was instrumental in switching seamlessly between admittance and impedance control modes according to real-time environmental stiffness estimates. This feature was particularly valuable in dealing with the significant changes in environmental stiffness during door opening, from free space to stiff contact with massive objects.

2) Predictive Anti-Slip Logic: The predictive approach for maintaining grasp stability using load prediction and Stribeck friction models was highly effective in keeping slip percentages below 15%. This approach was more effective than traditional reactive control strategies in maintaining stability.
3) 3Multi-Phase Task Orchestration: The finite state machine with deliberate pauses at 30° and 60° was effective in accumulating adequate forces while ensuring that peak forces were well below safety limits (actual 90 N vs. limit 150 N). This hierarchical approach effectively decomposed the complex task into simpler phases with clear safety milestones.
4) Comprehensive Validation: Realistic simulation with realistic door dynamics (solid oak, 40 kg) and performance metric logging were effective in validating that the task was completed in 12.35 s with all safety and performance metrics satisfied. A comparison with other approaches (baseline admittance and impedance control) also demonstrated the effectiveness of the proposed approach.
5) Safety Compliance: Safety compliance is ensured through the integrated safety architecture, which includes inherent compliance, predictive safety, and hard limits. This ensures compliance with the ISO/TS 15066 standard, which is applicable to collaborative robots. This is achieved through the layered safety concept, which ensures that no single point of failure compromises safety.

A. Future Work

Several directions for future research are identified:

1) Real-World Validation: The next step would be to implement the proposed controller on the hardware (Kinova Jaco robot with Robotiq gripper) and validate the performance on various doors with different properties (mass, friction, door stiffness).
2) Learning-Based Adaptation: Learning-based adaptation of the control parameters using machine learning can also be incorporated to improve performance on various doors with different properties.
3) Coordinated Base-Arm Motion: Expanding the framework to include coordinated motion of the mobile base with the robot arm can be useful for opening doors that require larger workspaces or doors that need to be pushed from behind.
4) Multi-Robot Collaboration: Another possible extension of the proposed framework is to consider collaborative door opening using multiple mobile manipulator robots, which can be useful for opening extremely heavy doors or for doors with complex locking mechanisms.
5) Human-Robot Co-Manipulation: Expanding the framework to consider human-robot co-manipulation of doors, where both human and robot contribute to the force, can increase the versatility of the framework.
6) Generalization to Other Tasks: The proposed framework for adaptive switching control can be generalized to other robotic tasks involving contacts, such as opening a drawer, turning a valve, or assembly tasks.

In conclusion, this work advances the state of the art in safe mobile manipulation by presenting an integrated framework that combines adaptive compliance control, predictive safety, and hierarchical task planning. The successful simulation validation demonstrates the framework's potential for enabling collaborative robots to perform complex manipulation tasks in human-shared environments while maintaining rigorous safety standards.

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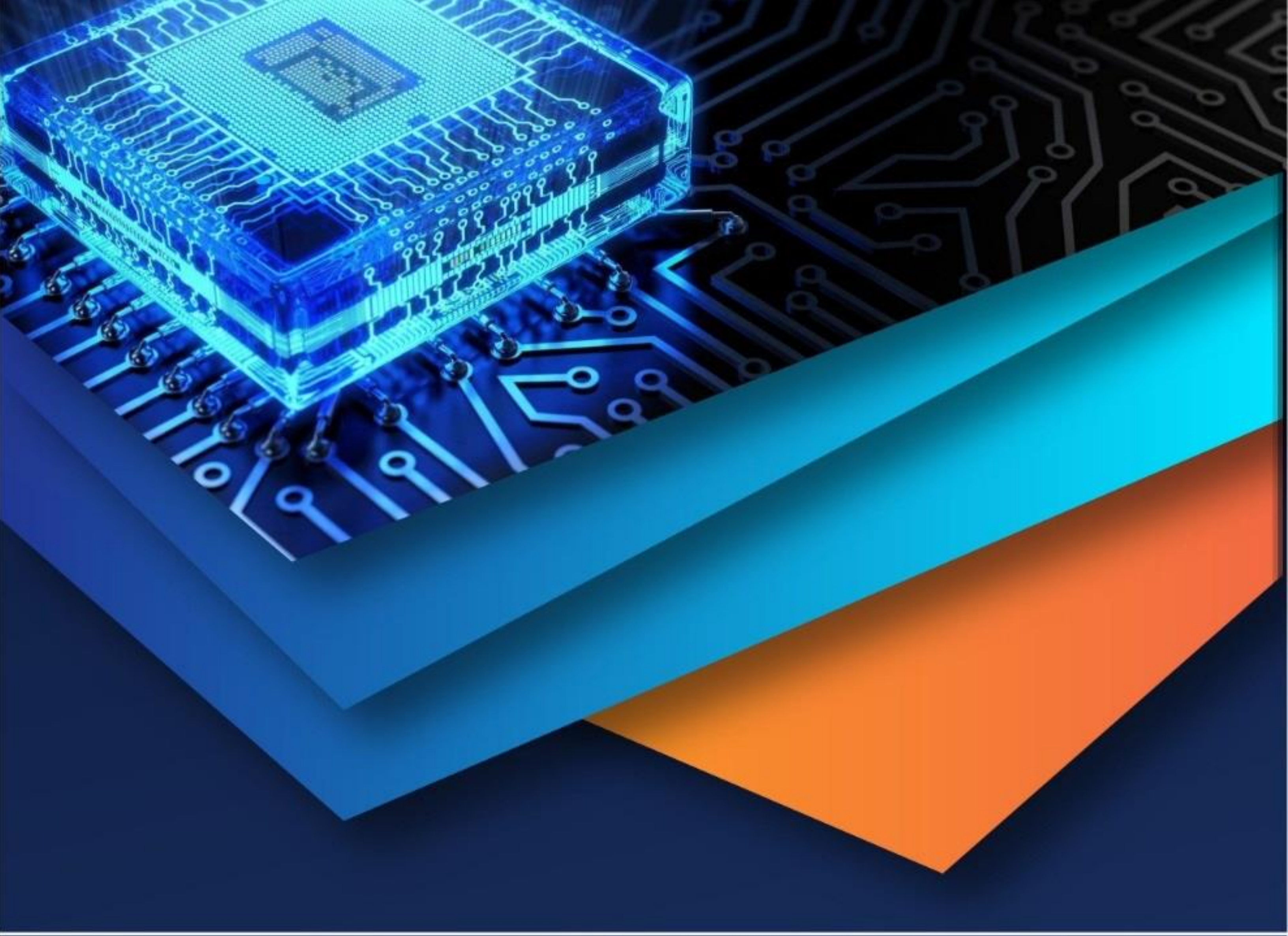

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