Flow Distributor Algorithm in High-Payload Hydraulic Manipulators for Nuclear Accident Response Operations

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1. Introduction

In recent years, the number of disasters has increased, a trend driven by rapid climate change and urbanization. As a result, there has been growing interest in robots capable of performing tasks in extreme environments[1].

In this context, 'ARMstrong,' a hydraulic manipulator, was developed by the Korea Atomic Energy Research Institute (KAERI) for emergency response operations in compact spaces with high payloads[2].

Conventional hydraulic robot controllers ignore flow constraints, leading to flow saturation when demand flow exceeds the maximum supply. Flow saturation causes uneven flow distribution based on actuator loads, resulting in unintended end-effector motion[3].

This study proposes a flow saturation prevention algorithm that can be incorporated as a compensator following a PID controller. Furthermore, the algorithm reduces end-effector tracking error by incorporating physical actuator properties, such as cylinder size and push/pull direction.

2. Control Design

The ARMstrong robot utilizes a position-based controller, which is composed of four main components: a PID controller, a Length Converter, a Flow Estimator, and a Flow Distributor.

The Length Converter converts the reference position and current joint position into cylinder lengths to calculate the length-based error. By using a length-based error for control, the nonlinearity between the controller's input and output is mitigated.

Based on the computed error, the PID controller generates the control input (u). This input is transmitted to the Demand Flow Estimator to calculate the demand flow (Q_{demand}) for each joint. Simultaneously, the supply flow (Q_{supply})is estimated from the rotational speed N_{hpu} of the Hydraulic Power Unit (HPU).

The Flow Distributor adjusts the control input u to ensure the total demand flow does not exceed the available supply flow. The resulting compensated input u_{dt} is then applied to the hydraulic valves to actuate the robot.

3. Flow Distribution Algorithm

The flow distribution algorithm is implemented in two versions. Version 1 applies a single, computed scaling factor (k_{fd}) uniformly to all joints, reducing their flow proportionally. In contrast, Version 2 differentially redistributes the flow based on each joint's individual error volume ($Volume_{err,i}$) and demand flow ($Q_{demand,i}$) with the objective of equalizing the convergence time across all joints.

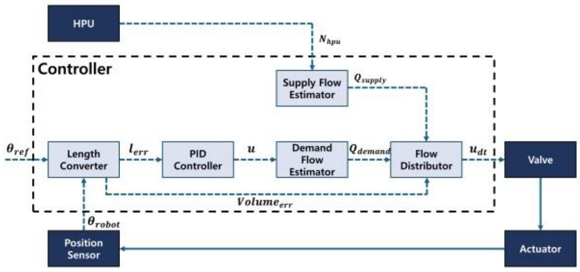

Fig. 1. ARMstrong Robot Controller Design

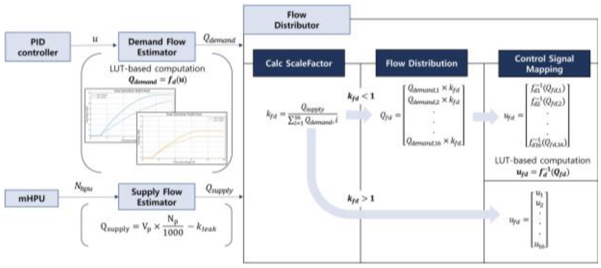

Fig. 2. Flow Distributor Algorithm version 1

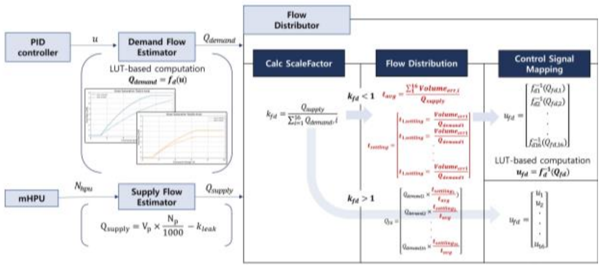

Fig. 3. Flow Distributor Algorithm version 2

4. Experiment and Result

4.1 Step Input Test

A Step Input Test was conducted to evaluate the effect of the Distributor Algorithm on joint behavior. Figures 5–7 show the response of a single manipulator arm (axes R1–R8) to a simultaneous 0° to 20° step input applied to all joints.

When the Distributor (DT) algorithm was deactivated, the system pressure dropped sharply from 100 bar to below 20 bar due to flow saturation. Consequently, the joint velocities varied depending on the hydraulic resistance of each axis (Fig. 4).

Using DT ver. 1.0, the system pressure was maintained at approximately 90 bar, successfully preventing flow saturation. This method reduced the extreme joint velocity differences caused by flow saturation. However, variations in convergence time were still observed, as each joint's convergence capability differs due to factors like varying loads and individual PID gains (Fig. 5).

In contrast, DT ver. 2.0 allocated flow differentially based on convergence rates, ensuring all joints converged at nearly the same time (Fig. 6).

4.2 Triangle Path Test

A Triangle Path Test was performed to validate the Distributor Algorithm's performance. The experiment compared the robot's trajectory tracking with the algorithm disabled and with DT ver. 2.0 enabled, as the end-effector traced a triangular path.

As shown in Figure 8, DT ver. 2.0 reduced the end-effector tracking error compared to when the distributor was disabled. The blue-shaded regions highlight periods where flow saturation caused pronounced tracking errors when the distributor was disabled. DT ver. 2.0 considerably mitigated the error in these regions.

Figure 8 shows the experiment's tracking error and end-effector velocity. DT ver. 2.0 demonstrated a reduced error while maintaining a comparable velocity, improving control accuracy without sacrificing performance.

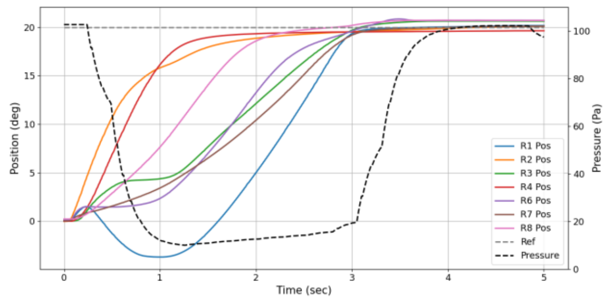

Fig. 4. Step Input Test (Distributor Disabled)

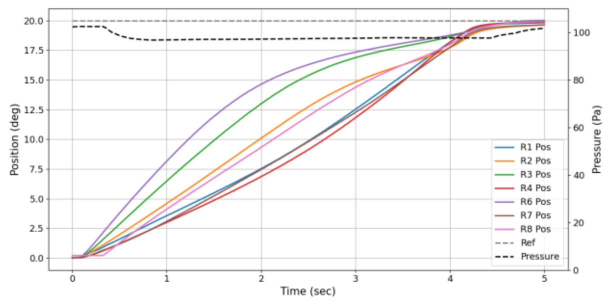

Fig. 5. Step Input Test (Distributor ver1 Enabled)

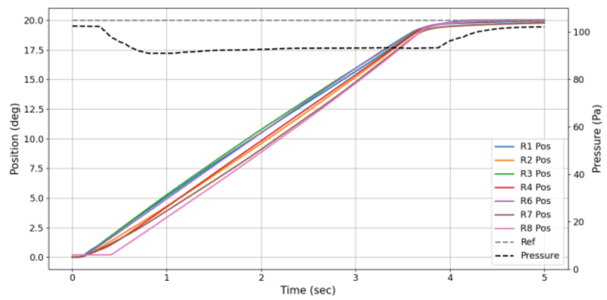

Fig. 6. Step Input Test (Distributor ver2 Enabled)

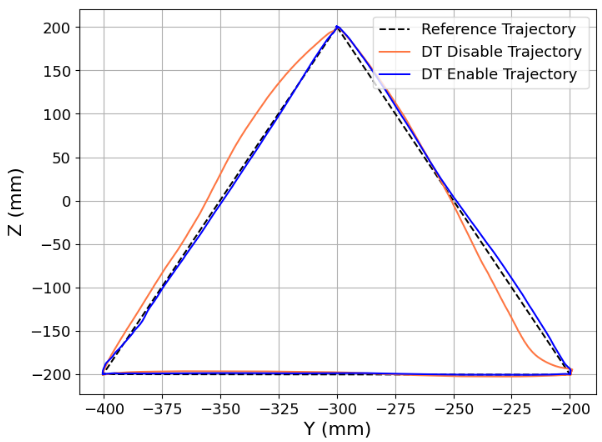

Fig. 7. Triangle Path Tracking Test Trajectory (Distributor Disabled, Distributor ver2)

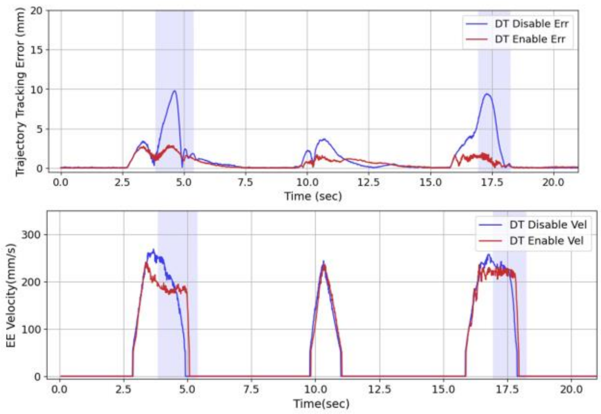

Fig. 8. Triangle Path Tracking Test Tracking Error, End Effector Speed (Distributor Disabled, Distributor ver2)

5. Conclusions

This study proposes a flow saturation prevention algorithm that acts as a compensator for PID controllers. Validated on the ARMstrong robot, the algorithm predicts supply and demand flows to adjust the control input, ensuring stable operation of the hydraulic manipulator. Experiments show the algorithm mitigates the imbalance in convergence capabilities between axes, thereby reducing the end-effector's tracking error. Compared to a PID controller, it effectively reduces tracking error without reducing velocity.

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