HYBRID TYPE-1 AND 2 FUZZY SLIDING MODE CONTROL OF THE INDUCTION MOTOR

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This paper focuses on developing two innovative induction motor (IM) control techniques. These techniques are based on the hybridization of Lyapunov theory (sliding mode) and artificial intelligence (type 1 and type 2 fuzzy logic). We will then compare these two control techniques to determine which is more robust. This comparative analysis will be based on a series of tests that we have carried out, covering the system's transient and steady-state operations under identical conditions. The first test involves observing the simulation results obtained by applying these control techniques to the motor to control the generated mechanical power. This qualitative comparison enables these controls to be evaluated for and without the application of external variations. The second test quantifies the different control laws based on quantified measurements, highlighting the performance of each technique in terms of error and time. This test is called a quantitative comparison. Finally, the last examination involves altering the machine parameters, as these values naturally experience fluctuations caused by diverse physical phenomena like inductance saturation and heating of the resistors. This comparison enables the robustness of the control techniques to be assessed.

1. INTRODUCTION

Today, the use of induction machines in industry is crucial, particularly in drive motors. This importance has prompted experts in the field to undertake in-depth research to improve the efficiency of these motors by optimizing energy transfer. This requires implementing appropriate control techniques capable of compensating for the internal and external disturbances affecting our machines. This research aims to ensure these motors operate optimally and reliably in a demanding industrial environment [1–3].

Among the various control techniques used to control our machine, sliding mode control stands out for its adaptability to systems with variable structures. The basic idea of this approach is to constrain and draw the system's dynamics (state) to a specifically chosen region, called the sliding surface, to design a control law that will constantly keep the system within this region. This way, precise and stable control can be guaranteed, even when system conditions change [4–6].

On the other hand, fuzzy logic-based control, whether type 1 or 2, is a control technique that exploits rules to deal effectively with uncertainties and non-linearities. This approach is based on the use of linguistic variables and fuzzy rules to approximate human-like decision-making processes. In this way, adaptive and robust control can be achieved, adapting to variations and changing conditions in the system. Thanks to this method, it is possible to achieve precise and reliable control, even in complex and unpredictable environments [7–9]. The combination of the strengths of sliding mode control and fuzzy logic control has attracted increasing interest in recent years, resulting in an innovative control strategy known as hybrid control. This approach seeks to exploit the advantages of both control techniques to improve performance, increase robustness, and ensure greater adaptability to induction machine systems. By synergistically combining the characteristics of the two approaches, hybrid control offers the potential to achieve superior results. It provides precise and responsive control, capable of effectively managing the uncertainties, non-linearities and variations inherent in the operation of induction motors. Thanks to this innovative control strategy, it is possible to significantly improve the performance and efficiency of industrial systems based on induction machines [10–12].

This paper presents a new hybrid control approach that combines two control techniques: sliding mode and type 1 and 2 fuzzy logic. We aim to achieve continuous and precise control of the mechanical power produced by the induction machine with almost zero tracking error and to ensure the system's robustness and stability. This innovative approach has resulted in high efficiency and optimum transmission quality.

In the first part, we presented the modeling of our machine and its bidirectional converters. In the second part, we discussed the control techniques used to control and optimise the mechanical energy generated by our machine. To this end, we have developed the following sliding mode control I based on the choice of sliding surface and convergence condition. This approach has enabled us to create a suitable control law to bring the errors between these surfaces and their controlled values toward zero. In this way, we ensure the instant stability and equilibrium of the system. II: The second control is based on hybridizing two control techniques: sliding mode and type 1 fuzzy logic. We have replaced the "sign" functions with type 1 fuzzy controllers to solve the interference problems III. The third control is also based on hybridizing two techniques: sliding mode control and type 2 fuzzy logic. This approach aims to improve the system's tracking qualities and obtain results with fewer static errors. Finally, the last part of our work is devoted to a comparative study of these control techniques. The aim is to highlight their effectiveness and robustness. This study relies on three fundamental criteria evaluated during transient and steady-state operations.

2. MODELLING OF THE MACHINE AND ITS CONVERTERS

It is necessary to model our machine and its converters individually to simulate the IM's behavior in different situations and to understand the control techniques that govern it.

2.1 IM MODEL

The induction motor is a highly complex, non-linear system. Accurate mathematical modeling is essential to effectively control its various operating modes. This

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approach provides a satisfactory and realistic representation of its behavior. The following expressions represent the mathematical model of the IM in the Park reference frame linked to the rotating field [13–17]:

\[
\begin{align*}
\frac{dI_d}{dt} &= -\frac{1}{L_d} \left( R_d I_d + \frac{M^2}{L_t} I_d + V_d + \cdots \right) \\
\frac{dI_q}{dt} &= -\frac{1}{L_q} \left( R_q I_q + \frac{M^2}{L_t} I_q + V_q + \cdots \right) \\
\frac{dV_d}{dt} &= -\frac{1}{L_d} \left( R_d I_d + \frac{M^2}{L_t} I_d + V_d + \cdots \right) \\
\frac{dV_q}{dt} &= -\frac{1}{L_q} \left( R_q I_q + \frac{M^2}{L_t} I_q + V_q + \cdots \right)
\end{align*}
\]

(1)

2.2 STATOR-SIDE CONVERTER MODEL

We must use a static converter, such as an inverter, to drive our variable speed motor and supply the machine's stator. The primary aim of this converter encompasses transforming the dc bus voltage into a suitable voltage for energizing the stator winding while enabling the implementation of directives to govern the mechanical power generated by the motor. The two-level converter consists of three arms, each fitted with two switches. Each switch is associated with a recovery diode mounted in antiparallel with the corresponding controllable semiconductor. The mathematical model of the stator side converter is [18–20]:

\[
\begin{bmatrix}
V_A \\
V_B \\
V_C
\end{bmatrix} = \frac{E}{6} \begin{bmatrix}
2 & -1 & -1 \\
-1 & 2 & -1 \\
-1 & -1 & 2
\end{bmatrix} \begin{bmatrix}
S_1 \\
S_2 \\
S_3
\end{bmatrix}
\]

(2)

2.3 GRID-SIDE CONVERTER MODEL AND CONTROL

The Grid-side (GSC) offers a major advantage: it controls active power while maintaining the dc bus voltage at a constant value. In addition, it sets the reference reactive power to zero, which avoids any deterioration in the quality of the network (a unitary power factor) [21,22]:

The structure of a grid-side converter can be deconstructed into three crucial components: the energy source, the converter unit, and the connected output. The equations describing the models of these elements are as follows:

\[
\begin{bmatrix}
\frac{dI_1}{dt} \\
\frac{dI_2}{dt} \\
\frac{dI_3}{dt}
\end{bmatrix} = \begin{bmatrix}
-\frac{R}{L} & 0 & 0 \\
0 & -\frac{R}{L} & 0 \\
0 & 0 & -\frac{R}{L}
\end{bmatrix} \begin{bmatrix}
I_1 \\
I_2 \\
I_3
\end{bmatrix} + \begin{bmatrix}
\frac{V_1 - V_{in}}{L} \\
\frac{V_2 - V_{bn}}{L} \\
\frac{V_3 - V_{cn}}{L}
\end{bmatrix}
\]

(3)

\[
\begin{bmatrix}
V_A \\
V_B \\
V_C
\end{bmatrix} = \frac{U_c}{3} \begin{bmatrix}
2 & -1 & -1 \\
-1 & 2 & -1 \\
-1 & -1 & 2
\end{bmatrix} \begin{bmatrix}
S_1 \\
S_2 \\
S_3
\end{bmatrix}
\]

(4)

\[
\frac{dU_c}{dt} = \frac{1}{C} (I_c - I_L)
\]

(5)

The GSC control can be implemented using a cascade control structure. Two internal loops are used to control the phase currents, while an external loop is used to control the output voltage. The voltages and powers used to perform this cascade control of our grid-side converter in Park's frame of reference are expressed by [22,23]:

\[
\begin{bmatrix}
V_{pd} \\
V_{pq}
\end{bmatrix} = \begin{bmatrix}
V_a - R I_d - L \frac{dI_d}{dt} + L o I_q \\
V_q - R I_q - L \frac{dI_q}{dt} - L o I_d
\end{bmatrix}
\]

(6)

\[
\begin{bmatrix}
P \\
Q
\end{bmatrix} = \frac{3}{2} \begin{bmatrix}
V_q I_d + V_i I_q \\
V_q I_d - V_i I_q
\end{bmatrix}
\]

(7)

2.4 MECHANICAL POWER BASED ON SLIDING MODE CONTROL

The dc voltage has the same profile as the imposed reference voltage. In addition, the line currents faithfully reflect the characteristics of the reference currents, which have sinusoidal shapes and are in phase with the line voltage. The results obtained successfully demonstrate the efficiency and robustness of current control in the (dq) reference frame of the GSC. This approach results in a significant reduction in harmonics and a significant improvement in the power factor.

3. MECHANICAL POWER CONTROL

To improve the efficiency of our induction motor through better energy transfer, we need to develop suitable control algorithms that can compensate for the effects of parametric and external disturbances, thereby optimizing the control of the mechanical power produced by our machine. To achieve this, we are developing three control strategies: Sliding mode control, Hybrid type-1 fuzzy sliding mode control, and Hybrid type-2 fuzzy sliding mode control.

3.1 MECHANICAL POWER BASED ON SLIDING MODE CONTROL

Sliding mode control is a recent approach to controlling non-linear systems with variable structures. This control method ensures results with fewer static errors and a fast, accurate response and is known for its stability and robustness. This control aims to control the rotational speed generated by the IM to that of a reference [24–27]. The fundamental concept of this control lies in the obligation and attraction of the dynamics (state) of the system towards a specifically defined zone, called the "sliding surface". A control law is then designed to keep the system constantly within this zone, thus guaranteeing optimal and stable control [28–30]. The model used, equations (1), is all expressed in a fixed frame of reference linked to the stator at Park reference frame (d,q).

To apply our control technique. We need to choose three sliding surfaces as follows:

- The speed surface
  \[ s(\Omega) = \Omega_{ref} - \Omega \]

- Direct stator current surface
  \[ s(I_{sd}) = I_{sd} - I_{sd} \]

- Quadrature stator current surface
  \[ s(I_{sq}) = I_{sq} - I_{sq} \]

All three sliding surfaces must be zero for the selected variables to converge to their reference values.


\[
\begin{align*}
\dot{s}(\Omega) &= \Omega_{\text{ref}} - \Omega (15); \quad \dot{s}(\Omega) = \dot{\Omega}_{\text{ref}} - \dot{\Omega} (16) \\
\frac{\text{d} \dot{I}_{\text{sd}}}{\text{d}t} &= \frac{P}{L_{s}} (\varphi_{rd} I_{\text{sq}}) - \frac{C_{r}}{I} + \frac{f}{J} \Omega (17)
\end{align*}
\]

Replacing the derivative of the velocity in equation (16) becomes

\[
\begin{align*}
\dot{s}(\Omega) &= \dot{\Omega}_{\text{ref}} - \frac{P}{L_{s}} (\varphi_{rd} I_{\text{sq}}) - \frac{C_{r}}{I} + \frac{f}{J} \Omega = -v_{r} \text{sign}(s(\Omega)) (18) \\
\dot{s}(\Omega) &= \dot{\Omega}_{\text{ref}} - \frac{P}{L_{s}} (\varphi_{rd} I_{\text{sq}}) - \frac{C_{r}}{I} + \frac{f}{J} \Omega = -v_{r} \text{sign}(s(\Omega)) (19)
\end{align*}
\]

The expression for the quadrature current slip surface and its derivative is

\[
\begin{align*}
\dot{s}_{\text{sq}} &= \frac{P}{L_{s}} (\varphi_{rd} I_{\text{sq}}) - \frac{C_{r}}{I} + \frac{f}{J} \Omega (20) \\
\dot{I}_{\text{sq}} &= \frac{P}{L_{s}} (\varphi_{rd} I_{\text{sq}}) - \frac{C_{r}}{I} + \frac{f}{J} \Omega (21)
\end{align*}
\]

\[
\begin{align*}
\dot{I}_{\text{sq}} &= \frac{P}{L_{s}} (\varphi_{rd} I_{\text{sq}}) - \frac{C_{r}}{I} + \frac{f}{J} \Omega (22)
\end{align*}
\]

Replacing the current derivative in eq. (25) becomes

\[
\begin{align*}
\dot{s}(I_{\text{sd}}) &= \dot{I}_{\text{ref}} - \dot{I}_{\text{sd}} (24); \quad s(I_{\text{sd}}) = I_{\text{ref}} - I_{\text{sd}} (25) \\
\dot{I}_{\text{sq}} &= -\frac{1}{L_{s}} \left( R_{s} + \frac{R_{m}^{2}}{L_{r}} \right) I_{\text{sq}} - w_{s} I_{\text{sd}} + \frac{M_{r}}{L_{s} L_{r} \sigma \varphi_{rd} W + \frac{1}{\sigma_{s}} v_{\text{sq}}} (26)
\end{align*}
\]

Replacing the current derivative in eq. (25) becomes

\[
\begin{align*}
\dot{s}(I_{\text{sd}}) &= \dot{I}_{\text{ref}} - \dot{I}_{\text{sd}} (24); \quad s(I_{\text{sd}}) = I_{\text{ref}} - I_{\text{sd}} (25) \\
\dot{I}_{\text{sq}} &= -\frac{1}{L_{s}} \left( R_{s} + \frac{R_{m}^{2}}{L_{r}} \right) I_{\text{sq}} - w_{s} I_{\text{sd}} + \frac{M_{r}}{L_{s} L_{r} \sigma \varphi_{rd} W + \frac{1}{\sigma_{s}} v_{\text{sq}}} (26)
\end{align*}
\]

By replacing the current derivative in eq. (33):

\[
\begin{align*}
\dot{s}(I_{\text{sd}}) &= \dot{I}_{\text{ref}} - \dot{I}_{\text{sd}} (24); \quad s(I_{\text{sd}}) = I_{\text{ref}} - I_{\text{sd}} (25) \\
\dot{I}_{\text{sq}} &= -\frac{1}{L_{s}} \left( R_{s} + \frac{R_{m}^{2}}{L_{r}} \right) I_{\text{sq}} - w_{s} I_{\text{sd}} + \frac{M_{r}}{L_{s} L_{r} \sigma \varphi_{rd} W + \frac{1}{\sigma_{s}} v_{\text{sq}}} (26)
\end{align*}
\]

Equations (31) and (39) are used to construct a sliding mode control block diagram for our induction motor.

3.2 MECHANICAL POWER BASED ON HYBRID TYPE-1 FUZZY SLIDING MODE CONTROL

In the field of control of electromechanical converters, research activities are increasingly directed toward the application of hybrid control technologies. This control is an attractive solution for exploiting the advantages and eliminating the disadvantages of the two control techniques combined to improve performance, increase robustness and ensure high efficiency and optimum transfer quality. In what follows, we apply the hybridization between sliding mode control and type 1 fuzzy logic to eliminate the two main drawbacks of both controls: the chattering phenomenon caused by the equivalent part of the sliding control and the instability and long computation time of the fuzzy control. This has made it possible to develop a stable and robust control system that guarantees performance results. This control system is called "hybrid type 1 fuzzy sliding control". We used the same sliding mode control structure with the three sign functions modified by type 1 fuzzy controllers to apply this control to our motor.
We used triangular shapes with trapezoidal sides to select the membership functions for the fuzzification blocks of the error and its variation. As for the choice of membership functions for the defuzzification blocks of the control variation, we also chose triangular shapes. Below is a table that presents the inference rules employed to determine the control variable related to the current parameter.

<table>
<thead>
<tr>
<th>Rate of change of error</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NB</td>
</tr>
<tr>
<td>N</td>
<td>NB</td>
</tr>
<tr>
<td>NB</td>
<td>NB</td>
</tr>
<tr>
<td>PB</td>
<td>NB</td>
</tr>
<tr>
<td>PB</td>
<td>NB</td>
</tr>
<tr>
<td>PB</td>
<td>ZR</td>
</tr>
<tr>
<td>PB</td>
<td>ZR</td>
</tr>
</tbody>
</table>

### 3.3 MECHANICAL POWER BASED ON HYBRID TYPE-2 FUZZY SLIDING MODE CONTROL

In addition to the advantages offered by hybrid type-1 fuzzy sliding control (Fig. 4), hybrid type-2 fuzzy sliding control is of particular interest because of its potential to further improve the performance achieved by its predecessor. This evolution aims to guarantee even more accurate results, significantly reducing static errors and even faster response.

Regarding the choice of the shape of the membership functions of the fuzzification blocks of the error and its variation, we decided to use three fuzzy sets of Gaussian shapes. This choice was made because of the ability of Gaussian functions to effectively model non-linear relationships and manage uncertainties in the data. Similarly, we chose five Gaussian-shaped fuzzy sets for the control variation defuzzification block. These fuzzy sets have been carefully selected to capture different levels of control variation, allowing finer and more accurate control decisions to be made. Combining these two blocks will enable a fuzzy logic control approach that can adapt flexibly and robustly to various scenarios.

#### 4. COMPARATIVE ANALYSIS OF THE CONTROLS DEVELOPED

To evaluate the different control laws developed and synthesized for our engine, this paper's subject, we will conduct a comparative study of the different techniques implemented. This analysis of comparisons relies on three fundamental methodologies: qualitative, quantitative, and robust.

### 4.1 QUALITATIVE COMPARISONS

This comparison is based on the analysis of simulation results from the application of various control techniques developed specifically for our induction motor. This comparison is based on the analysis of simulation results obtained by applying different control techniques developed specifically for our induction motor. In this comparison, the machine is supplied to operate at a reference speed equal to the synchronous speed of the IM (314 rad/s). An external variation is applied as a resistive torque (Cr = 2 N.m) at time T = 1s.
this stage, the results show that the control of the hybrid type 2 fuzzy sliding mode control (H.2.F.SMC) in brown is the most responsive and closest to what is desired in red. It is followed by the hybrid type 1 fuzzy sliding mode control (H.1.F.SMC) and, finally, by the sliding mode control.

4.2 QUANTITATIVE COMPARISONS

This assessment is based on a comparative numerical analysis of the simulation results obtained by applying the various control techniques we have developed to our induction motor. This test is based on the evaluation of four performance criteria, which are mathematically defined by Integral error squared,

\[
ISE = \int_0^T e^2(t) \, dt 
\]

(40)

The absolute error value integral: \( IAE = \int_0^T |e(t)| \, dt \)

(41)

The time integral is multiplied by the absolute value of the error:

\[
ITAE = \int_0^T t \, |e(t)| \, dt 
\]

(42)

The integral of the time multiplied by the value of the squared error:

\[
ITSE = \int_0^T t \, e^2(t) \, dt 
\]

(43)

The results shown in Table 3 are determined within the range of the external variation application (resistive torque).

<table>
<thead>
<tr>
<th>Criteria</th>
<th>G-C</th>
<th>Elaborate control systems</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SM.C</td>
</tr>
<tr>
<td>ISE</td>
<td></td>
<td>6.4395</td>
</tr>
<tr>
<td>IAE</td>
<td></td>
<td>1.1318</td>
</tr>
<tr>
<td>ITAE</td>
<td></td>
<td>1.3175</td>
</tr>
<tr>
<td>ITSE</td>
<td></td>
<td>6.8555</td>
</tr>
</tbody>
</table>

The simulation results in the table above clearly show that the hybrid type-2 fuzzy sliding mode control best minimizes all the ISE, IAE, ITAE, and ITSE criteria. This is reflected in the lowest values between the generated mechanical speed and its reference. This is followed by the hybrid type-1 fuzzy sliding mode control and the sliding mode control, respectively.

4.3 ROBUSTNESS COMPARISONS

The final test evaluates the developed controls' robustness by investigating how the induction motor's internal parametric variations affect their effectiveness. These parameters are subject to variations in practical scenarios due to various physical phenomena such as inductance saturation and resistance heating. In this experiment, we have varied the following parameters:

- The rotor resistance \( R_r \) is multiplied by 2, and the rotor inductance \( L_r \) is divided by 2. The parameter variation is performed in the time range from \( t = 1.5 \) s to \( t = 2.5 \) s.
- The matrix representation can succinctly express the standard state model for IM as:

\[
\dot{X} = \begin{bmatrix} I_{sd} & I_{sq} \\ \varphi_{rd} & \varphi_{rq} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_s} \end{bmatrix} \sigma \begin{bmatrix} R_r & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix} \begin{bmatrix} \frac{2}{L_s R_r} \varphi_{rd} \\ \frac{1}{L_q} \varphi_{rq} \end{bmatrix} \end{bmatrix} \begin{bmatrix} I_{sd} & I_{sq} \\ \varphi_{rd} & \varphi_{rq} \end{bmatrix} = \begin{bmatrix} I_{sd} & I_{sq} \\ \varphi_{rd} & \varphi_{rq} \end{bmatrix} \begin{bmatrix} \frac{1}{L_s} \sigma \begin{bmatrix} R_r & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix} \begin{bmatrix} \frac{2}{L_s R_r} \varphi_{rd} \\ \frac{1}{L_q} \varphi_{rq} \end{bmatrix} \end{bmatrix} 
\]

where: \( X = [I \sigma \varphi_e \varphi_q] \); \( U = [v_{sd} v_{sq}] \).

To apply the robustness test, the state model is decomposed as follows:

\[
\dot{X} = \begin{bmatrix} I_{sd} & I_{sq} \\ \varphi_{rd} & \varphi_{rq} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_s} \end{bmatrix} \sigma \begin{bmatrix} R_r & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix} \begin{bmatrix} \frac{2}{L_s R_r} \varphi_{rd} \\ \frac{1}{L_q} \varphi_{rq} \end{bmatrix} \end{bmatrix} \begin{bmatrix} I_{sd} & I_{sq} \\ \varphi_{rd} & \varphi_{rq} \end{bmatrix} = \begin{bmatrix} I_{sd} & I_{sq} \\ \varphi_{rd} & \varphi_{rq} \end{bmatrix} \begin{bmatrix} \frac{1}{L_s} \sigma \begin{bmatrix} R_r & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix} \begin{bmatrix} \frac{2}{L_s R_r} \varphi_{rd} \\ \frac{1}{L_q} \varphi_{rq} \end{bmatrix} \end{bmatrix} 
\]

(44)

As part of this comparison, we have assessed the robustness of the proposed controls by analyzing the variation in simulation results when faced with changes in machine parameters. This variation can be expressed qualitatively or quantitatively.

4.3.1 QUALITATIVE SIMULATION RESULTS

This comparison relies on examining the simulation results when confronted with parametric variations within the motor.
parametric variation points. This way, ISE, IAЕ, ITAE, and ITSE measurements highlight each control's performance and robustness, both in the presence and absence of internal and external variations. The results obtained from this comparative study show that type 2 fuzzy sliding hybrid control is the best-performing and most robust for our system compared with the other control techniques used.

### APPENDIX

#### Table 5

Simulation parameters of the IM (P = 0.79 kW)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_s$</td>
<td>10 $\Omega$</td>
<td>$L_s$</td>
<td>0.4642 H</td>
</tr>
<tr>
<td>$R_r$</td>
<td>6.3 $\Omega$</td>
<td>$L_r$</td>
<td>0.4612 H</td>
</tr>
<tr>
<td>$P$</td>
<td>2 $\Omega$</td>
<td>$f$</td>
<td>314 rad/s</td>
</tr>
<tr>
<td>$f$</td>
<td>0</td>
<td>$j$</td>
<td>0.02 kg m$^2$</td>
</tr>
</tbody>
</table>

### 5. CONCLUSIONS

In this paper, we have developed two control techniques based on the hybridization of Lyapunov theory (sliding mode control) and artificial intelligence (fuzzy logic control) to regulate the mechanical power generated by our induction motor. We will then conduct a comparative study between these two approaches to determine which performs better and is more robust, both in the presence and absence of internal and external variations. The results obtained from this comparative study show that type 2 fuzzy sliding hybrid control is the best-performing and most robust for our system compared with the other control techniques used.

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