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Exploration of the use of a proportional-integral-derivative controller for mitigation of seismic base excitation in civil structures

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ABSTRACT

Civil infrastructures are susceptible to damage due to external forces such as winds and earthquakes. These external forces cause damage to buildings and different civil structures. To prevent this, active control systems are executed. These systems use sensors to measure the displacement of the infrastructure, then actuators are utilized to provide a force that counteracts that displacement. In this study, a Proportional Integral Derivative (PID) controller was used to minimize the impact of an earthquake disturbance on multi-story structures. The proportional, integral, and derivative gains of the controller were obtained using Particle Swarm Optimization (PSO). This PID controller was validated on a simulated five-story structure based on the Kajima Shizuoka building with five ideal actuators. The effectiveness of the PID controller in reducing the seismic response of the structure with regards to inter-story displacement and acceleration was compared to the uncontrolled response of the structure. It is found that the PID controller with PID parameters obtained from the PSO algorithm offers effective control for the simulated five story structure.

Keywords: PID controller, Particle Swarm Optimization, structural control, civil structures

1. INTRODUCTION

Civil infrastructure, such as buildings, are prone to damage due to large external load events. These external forces cause damage to structures which can jeopardize the welfare of the community and occasionally cause death. This damage can be prevented through the use of active control techniques which seek to counteract the effects of external forces through an actuating device. These integrated systems have sensors that measure the structure's response, such as the displacement. A controller then uses this information to calculate the required force that would be necessary to counteract the undesired response. This command is then sent directly to the actuator by the controller.

To effectively implement these control systems, researchers have turned to using low power computing nodes as the controller node in order to create a more flexible system. In doing so, different control architectures can be embedded on these computing cores. For example, Swartz and Lynch explored using the Kalman Filter with a partially decentralized Linear Quadratic Regulator (LQR) to control a full-scale laboratory structure[1]. In another example, the H_∞ algorithm was distributed across multiple communication subnets of computing nodes and sophisticated state estimators were used[2]. Despite these studies indicating the advantages and success of the use of low-power control systems, several challenges arose due to the increase in computational complexity that in turn decreases the control effectiveness.

To address some of these challenges, researchers have turned to exploring a traditional control technique, the proportional-integral-derivative (PID) controller, for seismic excitation of buildings. PID control remains one of the most widely used control techniques due to its ease of implementation on a wide range of applications. For instance, PID control was compared to the LQR control on an 11 story structure[3]. It was determined that the PID controller had better performance as it reduced the maximum top story displacement, acceleration, and drift compared to the LQR. It was also found that the PID controller was sensitive to modeling errors as it maintained desired performance uncertainties in the control.

Despite the computational ease of the PID controller, acquiring control parameters for this algorithm when applied to civil structures proves to be challenging due to the off diagonal terms in the stiffness and damping matrices in such structures. This makes the traditional methods for obtaining PID control parameters often unsuccessful and ineffective. As such, researchers have turned to optimization algorithms such as the Particle Swarm Optimization (PSO) to derive control parameters for a PID control system. In one scenario, a PID controller, modeled as a single input-single output system,

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was used to alleviate the effects of loads on a high-way bridge[4]. The PID coefficients of the system were derived using the PSO algorithm. In another scenario, a new algorithm called slap swarm optimization was used to find the variables for a hybrid optimal PID-LQR controller and was validated on a four degree-of-freedom structure equipped with a damper[5].

While these studies demonstrate the successful use of PID, they assume the structure to be a single-input single-output system, which can over-simplify the problem. In this study, it is proposed to extend the complexity of the system and pair the PID control algorithm with the PSO on a structure using a multi-input, multi-output model. This study will investigate the effectiveness of this PID controller in controlling a five-story benchmark structure.

2. AMALGAMATION OF PID CONTROL AND PSO ALGORITHM

2.1 PID Control Algorithm

The PID controller integrates three terms to produce effective control results. In particular, the algorithm started with a simple proportional term, K_p, and then an integral term, K_I, was added to eliminate bias offset. A derivative term, K_d, is also included, as an anticipatory term. This results in the calculated control force, $u(t)$,

$$u(t) = \boldsymbol{K_P}\boldsymbol{e}(t) + \boldsymbol{K_I} \int_0^t \boldsymbol{e}(\tau)\, dt + \boldsymbol{K_D} \frac{d}{dt}(\boldsymbol{e}(t)) \tag{1}$$

where the $\boldsymbol{K_P}, \boldsymbol{K_I}, \boldsymbol{K_D}$ are the proportional gain matrix, integral gain matrix, and the derivative gain matrix for each floor respectively; $\boldsymbol{e}(t)$ is the difference between the desired response and the actual response for each floor. When applying this algorithm to seismic applications, the desired response is zero and as a result, the error term is just the negation of the actual structure response and in this case taken as the inter-story drift.

2.2 Particle Swarm Optimization Algorithm

Particle swarm optimization (PSO)[10], a computational method based on the idea of swarm intelligence, was used to optimize the PID parameters. In PSO, particles are randomly dispersed in a search space and each particle location is evaluated. The motion of each particle is steered by the particle's own best-known position along with the best-known position of the entire swarm. The process is repeated for numerous iterations as the swarm steers to the best possible solution. In order to determine the best possible solution, three vectors are tracked: the current position of the particle, the previous position of the particle, and its current velocity. As each particle interacts with other particles, the best position of the neighboring particles is stored in the vector $\boldsymbol{g}$. Equations 2 and 3 update the particle's position, $\boldsymbol{x}$, and velocity, $\boldsymbol{v}$, for each k^{th} iteration,

$$\boldsymbol{v_i}(k+1) = \lambda \boldsymbol{v_i}(k) + \rho_1\gamma_1\left(\boldsymbol{x_{b,i}}(k) - \boldsymbol{x_i}(k)\right) + \rho_2\gamma_2\left(\boldsymbol{g}(k) - \boldsymbol{x_i}(k)\right) \tag{2}$$

$$\boldsymbol{x}_i(k+1) = \boldsymbol{x_i}(k) + \boldsymbol{v_i}(k+1) \tag{3}$$

$$\lambda = \lambda \times \tau\ . \tag{4}$$

In these equations, ρ_1 and ρ_2 are random numbers between 0 and 1, i is the particle number, γ_1 and γ_2 are the acceleration coefficients which equals 2[11], λ is the inertia weight which controls the particle's convergence toward a solution[11], τ is the inertia damping constant and modifies the balance between local and global searches. For convergence of the particles, the inertia coefficient is initially set to 1 and then is reduced using the damping coefficient of 0.99[12]. After every iteration, the best solution (*i.e*, the best position) is assessed according to a defined objective function and the best position is updated if need be.

2.3 Cost Functions

In order to quantify the effectiveness of the PID controller in reducing the seismic response of the structure when using different gains obtained from the PSO, an objective function is needed. In this study, the minimization of five cost functions obtained from Ohtori et al.[13] are combined into an objective function. The first cost function, $\boldsymbol{J}_1$, quantifies the reduction in the maximum displacement of the structure,

$$\boldsymbol{J_1} = \frac{max(|\boldsymbol{d}(t)_{controlled}|)}{max(|\boldsymbol{d}(t)_{uncontrolled}|)} \tag{5}$$

such that $\boldsymbol{d}(t)_{uncontrolled}$ is the time history of the inter-story drift for all floors without any implementation of control, while $\boldsymbol{d}(t)_{uncontrolled}$ is the inter-story drift of all floors when subject to PID control, and $|\cdot|$ represents the absolute value function. The second cost function, $\boldsymbol{J}_2$, quantifies the reduction in the average displacement of the structure,

$$\boldsymbol{J_2} = \frac{\|\boldsymbol{d}(t)_{controlled}\|}{\|\boldsymbol{d}(t)_{uncontrolled}\|}. \tag{6}$$

The third cost function, $\boldsymbol{J}_3$, quantifies the reduction in the maximum acceleration of the structure,

$$\boldsymbol{J_3} = \frac{max(|\ddot{y}(t)_{controlled}|)}{max(|\ddot{y}(t)_{uncontrolled}|)} \tag{7}$$

where $\ddot{y}(t)_{uncontrolled}$ is the time history of the acceleration for all floors without any implementation of control while $\ddot{y}(t)_{controlled}$ is the acceleration of all floors when subject to PID control. The fourth cost function, $\boldsymbol{J}_4$, quantifies the reduction in the average acceleration of the structure,

$$\boldsymbol{J_4} = \frac{\|\ddot{y}(t)_{controlled}\|}{\|\ddot{y}(t)_{uncontrolled}\|}. \tag{8}$$

The fifth cost function is the ratio of the maximum time history of the control force for each floor and the seismic weight of the building based on the above ground mass of the structure and provides a quantification of the control effort,

$$\boldsymbol{J_5} = \frac{max(|\boldsymbol{f}(t)|)}{\boldsymbol{W_s}} \tag{9}$$

where $\boldsymbol{f}(t)$ represents the time history of the control force for each floor and $\boldsymbol{W}_s$ represents the seismic weight of the building based on the above ground mass of the structure.

The cost functions are used to optimize the PID parameters in the PSO algorithm and, therefore, must be combined into a single value, O. This is done by summing the five cost functions across all floors,

$$O = \sum_{l=1}^{m} J_{1,l} + J_{2,l} + J_{3,l} + J_{4,l} + 5J_{5,l} \tag{10}$$

where m represents the number of floors in the structure. $\boldsymbol{J}_1$, $\boldsymbol{J}_2$, $\boldsymbol{J}_3$, and $\boldsymbol{J}_4$ each have a value of 1.0 for all floors when the structure is uncontrolled. This means that sum of the cost function from $\boldsymbol{J}_1$ through $\boldsymbol{J}_4$ in the benchmark five-story structure is 20 in an uncontrolled scenario. On the other hand, it was found that $\boldsymbol{J}_5$ generally has a value of 0.2 or less; for this reason, $\boldsymbol{J}_5$ is multiplied by 5 so that it can be equally weighted as the other cost function. Hence, a cost function less than 25 denotes some effective control in the structure and the smaller the objective function, O, the more effective the control is.

3. VALIDATION OF PID CONTROLLER

3.1 Five-Story Benchmark Structure

A five-story structure based on the Kajima Shizuoka building was implemented in simulation in order to validate the proposed PID-PSO control. The setup was based on a structure used in a study conducted by Kurata et al[8] and is shown in Figure 1. Table 1 shows the properties of the benchmark structure, which yield the natural frequencies: 1.00, 2.82, 4.49,

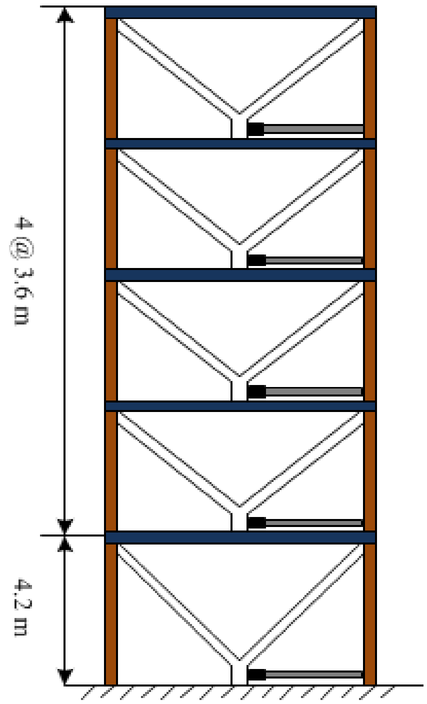

Figure 1: Schematic of the Kajima Shizuoka building

Table 1. Benchmark structure properties

Floor	1	2	3	4	5
Seismic mass (x10^3 kg)	215.2	209.2	207.0	204.8	266.1
Inter-story stiffness (x10^3 kN/m)	147	113	99	89	84

5.80, and 6.77 Hz. The damping in the structure was assumed to be a 5% damping ratio based on Rayleigh damping that is both mass-proportional and stiffness-proportional[9]. In this set up, it is assumed that each floor is equipped with a transducer that measures inter-story displacement and an ideal actuator that is capable of supplying the demanded control force.

The structure is modeled as an *m* degree-of-freedom system, whose dynamics can be generalized through *m* equations of motion[10],

$$\boldsymbol{M}\ddot{\boldsymbol{y}}(t) + \boldsymbol{C_d}\dot{\boldsymbol{y}}(t) + \boldsymbol{K_s}\boldsymbol{y}(t) = -\boldsymbol{M}\boldsymbol{\iota}\ddot{y}_g(t) + \boldsymbol{l}\boldsymbol{f}(t) \tag{11}$$

where $\boldsymbol{M}$ is the mass matrix, $\boldsymbol{C}_d$ is the damping matrix, and $\boldsymbol{K_s}$ is the stiffness matrix, all of which are mxm in size; $\boldsymbol{y} \in R^m$ is the displacement vector relative to the base of the structure, $\ddot{y}_g$is the ground acceleration and $\boldsymbol{\iota} \in R^m$ is the ground acceleration influence vector. Additionally, $\boldsymbol{f} \in R^p$ is a vector of control forces with p as the number of input control forces and $\boldsymbol{l} \in R^{mxp}$ describes the actuator's location. The uncontrolled response of each floor of this structure is approximated using Newmark's Method[10]; this is achieved when the control force, $\boldsymbol{f}$, is set to zero.

3.1 Application of PSO to determine PID parameters

To calculate the control force, the coefficients $\mathbf{K_P}$, $\mathbf{K_I}$, and $\mathbf{K_D}$ for each floor are optimized using the Particle Swarm Optimization (PSO), while minimizing the desired objective function (Equation 10). The particle, $\boldsymbol{x}$, was set up as a 1*15 vector of the form $[\mathbf{K_P}\ \mathbf{K_I}\ \mathbf{K_D}]$ where $\mathbf{K_P}$, $\mathbf{K_I}$, and $\mathbf{K_D}$ are 1x5 vectors with each entry corresponding to a floor. To determine the optimal particle, the five-story structure was subject to seismic base excitation from the 1940 El Centro earthquake (Figure 2). The response of the structure was modeled using equation 11 and Newmark's integration method[9]. For the PSO algorithm 50 particles were used to cover the search space. To confirm convergence of the algorithm, the particles were trained until a better solution was not found for 50 iterations. After the training was complete, the global best particle produced the cost functions shown in Table 2 with a total objective function of 9.811. In general, there is a significant reduction in the displacement metrics ($\boldsymbol{J}_1$ and $\boldsymbol{J}_2$) and a modest reduction in the acceleration metrics ($\boldsymbol{J}_3$ and $\boldsymbol{J}_4$). Figure 3 shows the time history of the displacement for both the uncontrolled and controlled scenarios for all five floors.

It was observed that in this scenario, the first floor experiences the largest inter-story drift and acceleration. Therefore, to ensure that it is necessary to have actuators on all five floors, the PSO algorithm was utilized to obtain optimized PID parameters for two other scenarios. For the first scenario, the actuator was placed on the first floor and the control force, $u(t)$, was calculated based on information from the first floor only. The sum of the cost functions was 16.126, or 39.2% larger than the cost function when the actuators are placed on each floor, making it less effective. In particular, there was a significant increase in the cost functions associated with inter-story drift (*i.e.*, $\boldsymbol{J}_1$ and $\boldsymbol{J}_2$). Detailed cost function values for this scenario are shown in Table 3. In the second scenario, the actuator was again placed on the first floor, but the control force, $u(t)$, was calculated based on information from all of the floors. The sum of the cost function was 24.319, 59.7% larger than the sum of cost function when the actuators are placed on each floor. A closer look at the

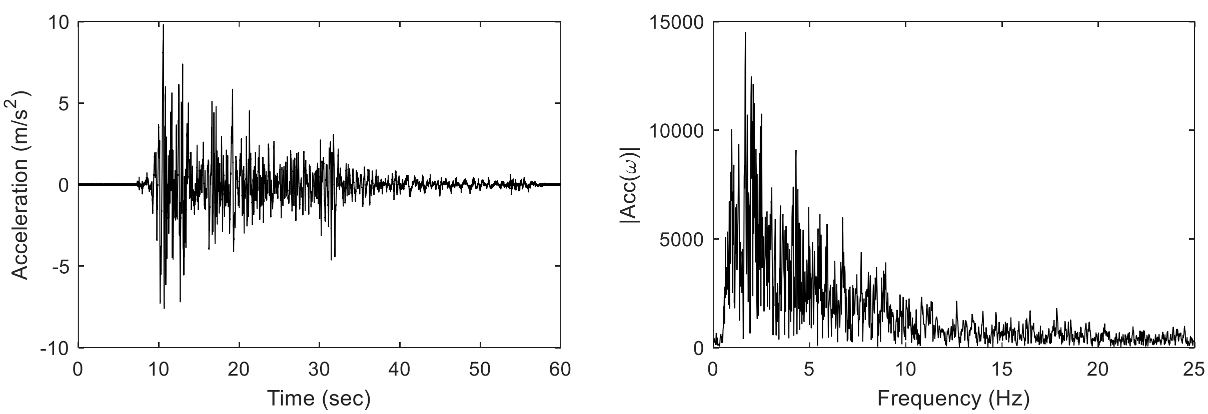

Figure 2. 1940 El Centro (Southeast) Earthquake in the time (a) and frequency (b) domains.

Table 2. Cost functions $\boldsymbol{J}_1$ through $\boldsymbol{J}_5$ for El Centro earthquake for the five-story structure

Floor	1	2	3	4	5
$\boldsymbol{J}_1$	0.143	0.072	0.107	0.102	0.067
$\boldsymbol{J}_2$	0.131	0.109	0.110	0.124	0.182
$\boldsymbol{J}_3$	0.803	0.683	0.588	0.598	0.446
$\boldsymbol{J}_4$	0.420	0.309	0.276	0.227	0.208
$\boldsymbol{J}_5$	0.163	0.151	0.160	0.189	0.157

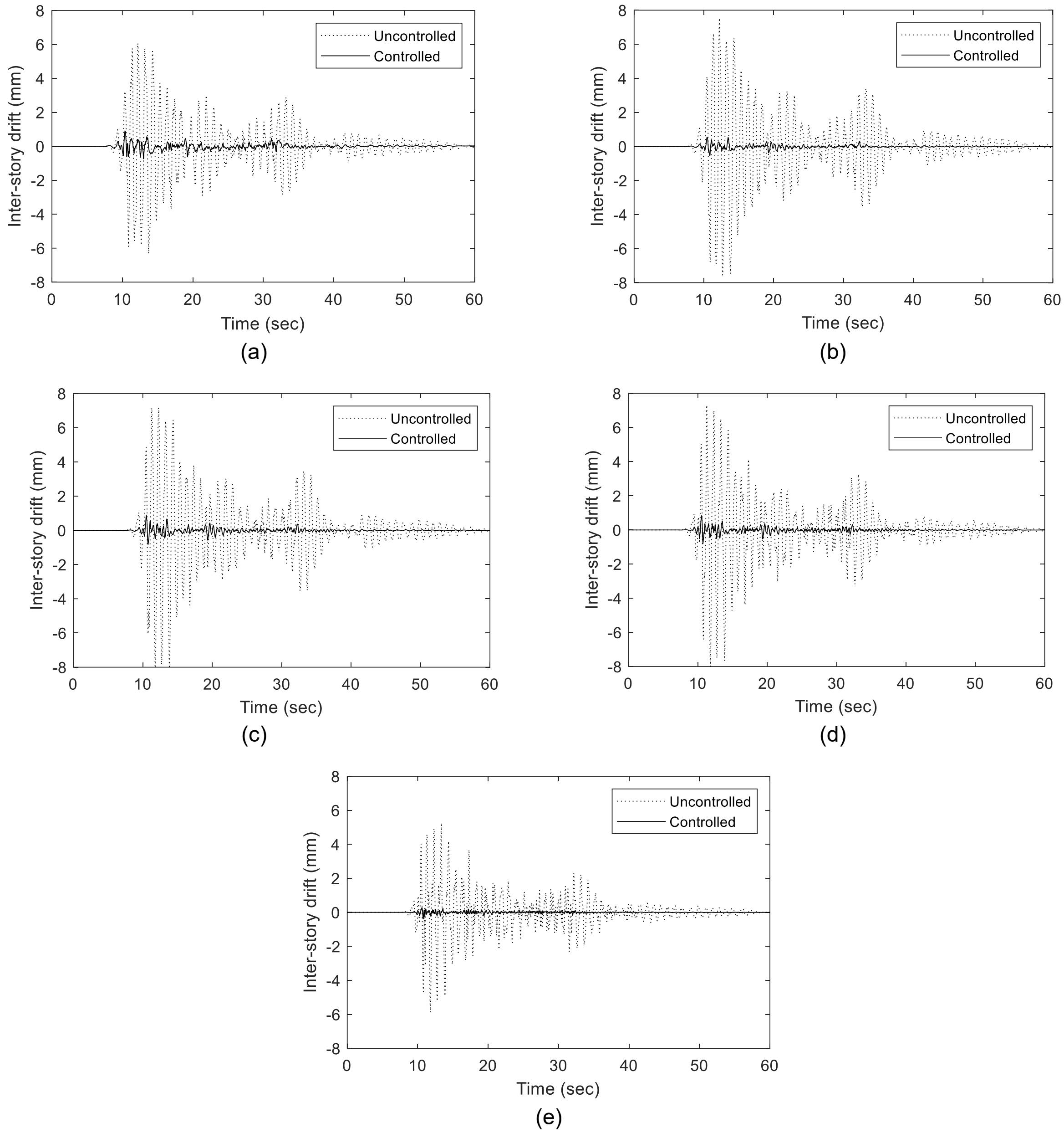

Figure 3. Time history response of inter-story drift for uncontrolled and controlled scenarios on floor 1 (a), floor 2 (b), floor 3 (b), floor 4 (d), and floor 5 (e).

individual cost functions (Table 4) shows that this control scenario was largely ineffective as most values are close to or larger than 1.0. From this, it can be concluded that PID control, when paired with the PSO algorithm, is effective in reducing the seismic response for systems using a multi-input, multi-output framework.

4. CONCLUSION

While PID control is a common control system used in industry, very few studies have utilized the PID controller for control in civil structures. The most successful use of PID control is seen in single-input, single-output scenarios where the actuator based its response only on the first floor's data. In this study, a PID controller was used to minimize the impact of an earthquake disturbance on a multi-story structure. The proportional, integral, and derivative gains of the controller

Table 3. Cost functions J_1 through J_5 for El Centro earthquake when the benchmark structure has an ideal actuator on the first floor and depends on drift and velocity information of the first floor.

Floor	1	2	3	4	5
J_1	0.742	0.432	0.454	0.534	0.567
J_2	0.722	0.597	0.602	0.683	1.002
J_3	0.905	0.641	0.713	0.747	0.611
J_4	0.507	0.539	0.560	0.564	0.546
J_5	0.184	-	-	-	-

Table 4. Cost functions J_1 through J_5 for El Centro earthquake when the benchmark structure has an ideal actuator on the first floor and depends on drift and velocity information of all five floors.

Floor	1	2	3	4	5
J_1	1.0116	0.8081	0.8278	0.8886	0.9529
J_2	1.8054	1.4934	1.5048	1.7086	2.5045
J_3	1.0299	1.0210	0.9876	0.8523	0.9651
J_4	1.1024	1.1273	0.9882	0.8466	0.9224
J_5	0.1940	-	-	-	-

were obtained using Particle Swarm Optimization (PSO). This PID controller was validated on a simulated five-story structure based on the Kajima Shizuoka building with five ideal actuators. When the effectiveness of the PID controller in reducing the seismic response of the structure was investigated with regards to inter-story displacement and acceleration, it was discovered that the PID control significantly reduced the effects of the earthquake.

In the future, the actuator dynamics will be implemented, instead of assuming ideal actuators, in order to investigate the performance of PID control in a more realistic environment. The ideal actuators do not reflect the realistic dynamics that may affect the execution of a control time step, and consequently would limit the amount of force applied by the actuators. While this study shows the success of the PID-PSO control, including these dynamics will allow for a more robust validation.

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