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Page count:	6
Word count:	3,595
Character count:	18,580
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Submission ID:	1807298454

2021 The 21st International Conference on Control, Automation and Systems (ICCAS 2021)
Ramada Plaza Hotel, Jeju, Korea, Oct. 12∼15, 2021

On a Proxy-Based Control as Multiple Controllers with Feedback Interconnections

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Abstract: A proxy-based control, in its core, is two controllers combined in series. This paper presents the fundamental aspects of such a unique control technique. We first establish the main features of a proxy-based control. These features are mainly related to the stability of a controlled system. Additionally, we propose a simple form of a proxy-based control and implement it into a test device for proof of concept. The simple proxy-based control that we propose in this paper is composed of two constant gains (proportional terms) and one integral term to remove the steady-state error. This integral term must be attached to the controller with the lower impedance. We also explore another feature of a proxy-based control during this hardware implementation: how we use one control gain to perform fine-tuning while using the other control gain to maintain system stability. We demonstrate this by adding an adaptation law also to the controller with the lower impedance. All obtained results align with the presented theory.

Keywords: Proxy-based control, System stability, Feedback interconnections, Adaptive control.

1. INTRODUCTION

A proxy-based control is relatively a new control method that was introduced in 2006 by Kikuuwe et al. (see [1], [2]). It has been implemented successfully in several other works, such as in [3], [4], [5], and [6]. To the best of the authors' knowledge, a proxy-based control has only been implemented in the field of robotics for motion control applications.

When first introduced, a proxy-based control combines two controls: a sliding mode control (SMC) and a proportional-integral-derivative (PID) control, where those two controllers are connected in series. It is more common to combine different controllers in parallel structures. Typically, the outputs from these different controllers enter a summing junction, and the result is then sent to the plant. The introduction of a proxy analogous to a mass with zero weight is why the two controllers can be used in one system. The way these controllers are connected is different from in a cascaded controller. A cascaded controller creates several feedback loops, e.g., inner loop and outer loop [7]. These loops do not exist in a proxy-based control.

The original paper in a proxy-based control focuses on a specific type of a proxy based-control, which the original authors named a proxy-based sliding mode control (PSMC). As we attempt to generalize the concept of a proxy-based control, we notice that it should also be possible to use control methods other than the original authors proposed. Moreover, employing more than two controllers should also be theoretically possible. Theoretical analysis on a proxy-based control, including its stability characteristics, can also be made general

As a proof of concept, we have implemented a simple proxy-based control to a linear system with time delay. We selected such a system because an inherently stable linear system can become unstable in the presence of time delay when feedback control is implemented into it (see [8]). This phenomenon is similar to motion control, where the actuators experience saturation and blocked movement. A proxy control is beneficial for such a system because of its inherently bounded control output.

This paper's contribution is in the investigation of basic principles of a proxy-based control, allowing it to be implemented in a more general situation. Simply put, this paper generalizes the concept of a proxy-based control. In doing so, we have expanded the application of a proxy-based control outside the field of robotics. Hence, we strengthen a proxy-based control's practicability, in addition to the existing in the original paper.

This paper organizes as follows. In Section 2 we explain the basic concept of a proxy-based control. In Section 3, we provide some examples of a proxy-based control. In Section 4, we propose a simple proxy-based control which we then implement in Section 5. Finally, in Section 6, we provide conclusion to our work.

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by Nur Uddin

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2. BASIC CONCEPT

To deliver the basic concept of a proxy-based control, let us first create an analogy in the mechanical domain. Later, we can expand the analogy to other domains as well. Fig. 1 shows the mechanical representation of a general proxy-based control. In a mechanical domain, a inherently stable system $W(s)$ is controlled by several interconnected controllers. Each controller is presented as a virtual mechanical impedance $(Z_1, Z_2, \dots, Z_n)$ that takes position/velocity as the input and sends force/torque as the output. These virtual mechanical impedances are interconnected serially. The total mechanical impedance can then be calculated as the inverse of the harmonic sum of each impedance:

$$\begin{aligned} Z_{\mathrm{tot}} &= \frac{1}{1/Z_1 + 1/Z_2 + \cdots + 1/Z_n} \\ &= \frac{Z_1 Z_1 \dots Z_n}{Z_1 + Z_1 + \cdots + Z_n} \end{aligned} \tag{1}$$

where all impedances are real valued and their values are defined by the amplitude and frequency of the applied input. Here, the concept of mechanical impedance is analogous to the concept of impedance in a resistor-inductor-capacitor (RLC) circuit in the field of electrical engineering [9].

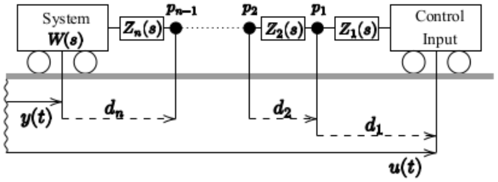

Fig. 1. Mechanical representation of a proxy-based control.

Fig. 1 can also be presented as Fig. 2. In Fig. 2, the serially connected virtual impedances are drawn as feedback interconnections. The connection order of the individual controller is irrelevant since it does not affect the resulting final controller. This can be seen clearly from Eq. 1.

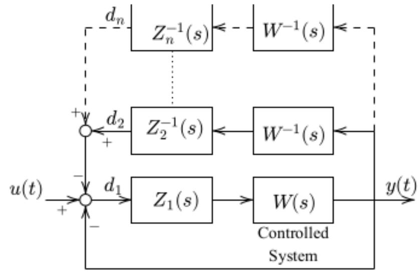

Fig. 2. Feedback interconnection in a proxy-based control.

As for its stability, a proxy based controller possess a unique characteristic that can be used to simplify its stability analysis. Let us start with the following remark. Any feedback interconnection can not cause an already stable feedback controlled system to become unstable.

Proof: To proof this remark, we use the mechanical analogy of a proxy-based control as shown in Fig. 3. Let us take $Z_{\mathrm{tot}-1}$ as the total impedance of Eq. 1 when one arbitrary impedance is removed, i.e., Z_1. Setting $|Z_1| = 0$ gives us the top figure. On the other hand, setting $|Z_1| = \infty$ give us the bottom figure. In other word, $Z_{\mathrm{tot}} = 0$ when $|Z_1| = 0$ and $Z_{\mathrm{tot}} = Z_{\mathrm{tot}-1}$ when $|Z_1| = \infty$. There is no value of Z_1 that can cause $Z_{\mathrm{tot}} > Z_{\mathrm{tot}-1}$. Since how the impedances are ordered is irrelevant, the other way around is also valid. ■

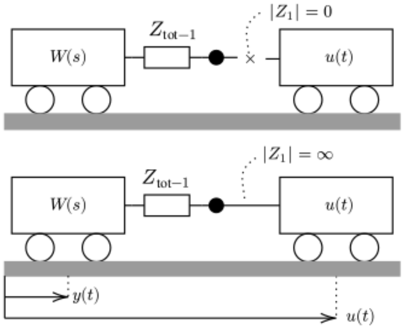

Fig. 3. A feedback interconnection that remains stable.

In simpler words, the value of the total impedance (Z_{tot}) tells us how stiff the controller is. The higher its value, the stiffer the controller becomes. Hence, the risk for the controlled system to go unstable is also higher. Since the total impedance of the controller is naturally bounded by the smaller individual controller impedance, we can guarantee the system's stability as long as the smaller impedance never causes the controlled system unstable.

3. PROXY-BASED CONTROL'S EXAMPLES

In this section, we discuss two control methods that can be classified as a proxy-based control. The first example is the original PSMC, which is composed of a PID and an SMC (see Fig. 4). The second example is the Smith predictor which is composed of a proportional control and a time delay predictor (see Fig. 5). As can be seen from their diagrams, both control methods have a feedback interconnection. The existence of a feedback interconnection becomes the indicator of a proxy-based control.

Since a PSMC and a Smith predictor are both proxy-based controls, we can calculate the total impedance for both controllers. In a PSMC, its total

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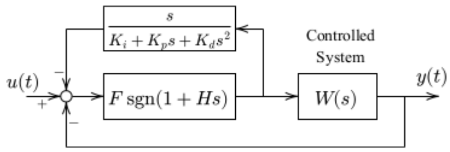

Fig. 4. A proxy-based control with a PID control and an SMC.

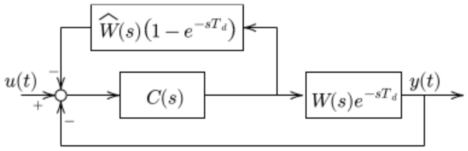

Fig. 5. The basic Smith predictor as a proxy-based control.

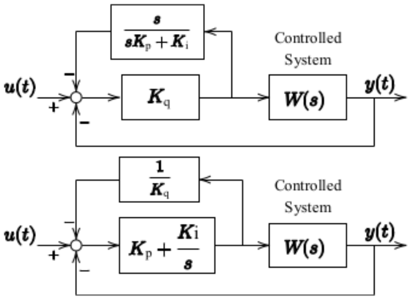

Fig. 6. The block diagram of the proposed proxy control (the upper figure is equivalent to the lower figure).

impedance can be calculated as follows:

$$Z_{\mathrm{tot}} = \frac{sF\mathrm{sgn}(Hs+1)}{(K_d s^2 + K_p s + K_i)\,F\mathrm{sgn}(Hs+1) + s} \tag{2}$$

where K_p, K_i and K_d are the parameters for the PID, which represent the gain for the proportional term, integral term and derivative term, respectively. F and H are the parameters for the SMC, which represent the SMC output saturation and proportional term, respectively.

As for a Smith predictor, its total impedance can be calculated as follows:

$$Z_{\mathrm{tot}} = \frac{\widehat{W}(s)(1 - e^{-sT_d})C(s)}{\widehat{W}(s)(1 - e^{-sT_d}) + C(s)} \tag{3}$$

where $W(s)$ and $\widehat{W}(s)$ are the actual and estimated system's model, respectively, T_d is the system's time delay, and $C(s)$ is the controller.

Now, since we have concluded that a PSMC and a Smith predictor both belong to the same controller family: a proxy-based control, stability analysis for those two controllers can be made simpler. We can easily remove the mathematically more complicated controls and analyze only one and much simpler control for the overall system's stability. analysis.

4. THE PROPOSED SIMPLE PROXY-BASED CONTROL

In this paper, we propose a simple proxy based control which combines a proportional control (P-control) and a proportional-integral control (PI-control) as shown in Fig. 6. Hence, there are three three tuning constants in the proposed control. They are two proportional constants (K_{p} and K_{q}) and one integral constant (K_{i}).

From Eq. 1, we can conclude that the controller with lower impedance will dominate the dynamics of the total controller Z_{tot}. For such a reason, the integral term must be attached to the P-control with a lower gain - in other words, the control with a lower impedance. Therefore, in Fig. 6, the value of K_{p} must be greater than the value of K_{q}.

Stability analysis can be performed by first removing the PI-control, leaving us with only with the P-control. Thus, a root locus technique can be used to guarantee that the selected gain for K_{q} does not cause the controlled system to become unstable. Additionally, modeling the system becomes necessary since $W(s)$ must be known in order to plot its root locus.

5. PROOF-OF-CONCEPT HARDWARE IMPLEMENTATION

This section presents the hardware implementation of the proposed proxy-control on a simple test device, which is an educational thermal device that we have previously developed. Here, we first start with the descriptions of the test device and then continue with the device modeling and control implementations.

5.1 Hardware Descriptions

The thermal device that is used in this paper was originally developed for teaching the dynamics and control course for upper-year undergraduate students in mechanical engineering. For such devices, there have been several quite similar devices reported in literatures (see [10], [11]). One of the requirements for the developed device is that the device must be inexpensive. On the other hand, it must have sufficient performance for temperature control implementations. Since the dynamic of temperature changes is relatively slow, the two main requirement can be fulfilled satisfactorily by the device that we have developed. .

The developed device is shown in Fig. 7. The device is built on a single board stacked on top of an Arduino Uno. It is comprised of two heaters whica are made of two power resistors (5 Watts/27 Ohms).

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On each heater an analog temperature sensors (LM 35) is mounted to measure the heater's temperature. Temperature of both heaters are controlled by an Arduino Uno (Arduino AG, Italy) which sends pulse width modulation signals (PWM), from 0% to 100%, to each heater through a transistor (IRLB 3034). When receiving a 0%-PWM signal, the heater does not heat up and the temperature eventually settles to the current room temperature. When the heater receives a 100%-PWM signal, the heater heats up to its maximum heating rate until it settles to its maximum temperature. However, in this research paper, only one of the heaters is actually used. Details on the developed thermal control device has been made available for public in [12].

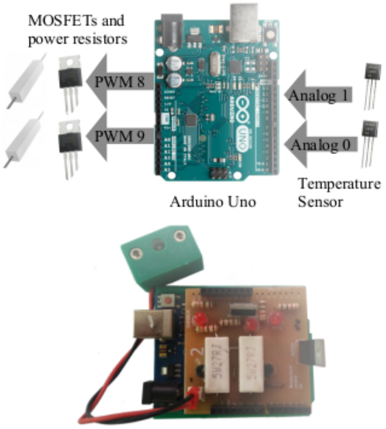

Fig. 7. The schematic (upper) and the developed (lower) temperature control device.

Throughout this paper, the programs for data collections and control algorithm are implemented in a computer running MATLAB and Simulink (The MathWorks, Inc., USA). The program is always set to the highest possible priority to create a soft real-time environment. The Arduino Uno is connected to the computer and it functions only as input-output server. All computations are running at 10 Hz with less than one percent jitter.

5.2 System Modeling

To model the heater, we use a linear second order model with a time delay. The final model's parameters are obtained form an optimization process. Since this optimization process requires initial parameter guesses, we perform Harriott's method [13], [14] for system identification and use the obtained values as the initial guesses. The optimized model that we have found is as follows:

$$W(s) = \frac{Y(s)}{U(s)} = \frac{e^{-10.2s}}{1622.5s^2 + 186.8s + 0.9} \tag{4}$$

where $Y(s)$ is the Laplace form of $y(t)$ and $U(s)$ is the Laplace form of $u(t)$. They represent the temperature of the heater and the applied PWM signal to the heater in Laplace domain, respectively. The performance of the developed model is summarized in Fig. 8.

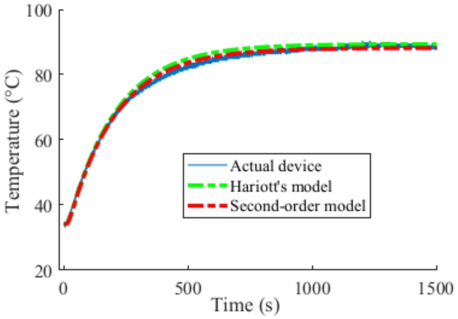

Fig. 8. Output of the model compared to the actual system's response.

Once we have calculated the model of the system, we can then generate the root locus plot of the system. This can be easily done by using the MATLAB rlocus command. However, the rlocus command can only take linear function as its input. Therefore, we must first perform Pade approximation [15] to eliminate the exponential function from Eq. 4. For the system that we use, the approximated model is found to be as follows:

$$\frac{Y(s)}{U(s)} = \frac{-s + 0.2}{1622s^3 + 504.9s^2 + 37.5s + 0.2} \tag{5}$$

As for the root locus plot of Eq. 5, we present the plot in Fig. 9. From this root locus plot, we know that one of the gain for the proposed proxy-based control must be less than 21. In most control system textbooks, such a gain is known as the $j\omega$-crossing gain.

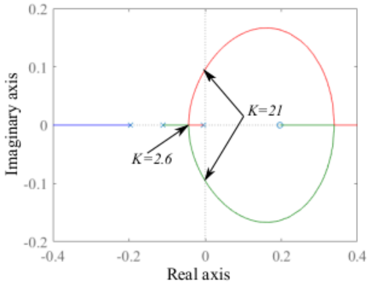

Fig. 9. Root locus of the linearized system.

5.3 Control Implementations and Results

In this section we conducted two experiments. In the first experiment, we implemented the proposed simple proxy-based control that we have already described in Section 4 (see Fig. 10). In the second experiment, we added a simple adaptation law based

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on the work of Seraji [16] to the control with lower impedance (see Fig. 11). The adaptation law modify the gain linearly based on the current error value. As the result, when the error is larger, the control impedance increases, and vice versa. The purpose of the second experiment is merely to demonstrate that with the proposed proxy-based control, we can modify one controller without risking system's stability. Here, the stability is guaranteed by another controller with higher impedance.

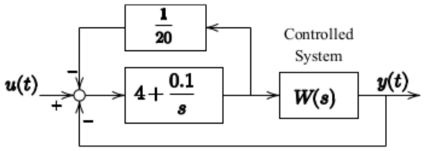

Fig. 10. The implemented proxy-based control.

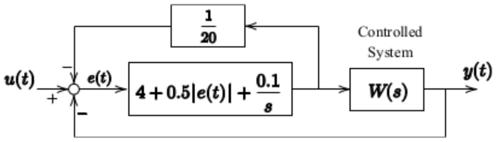

Fig. 11. An adaptation law is added to the control with lower impedance.

In both experiments, a step input with an amplitude of 50 degrees Celcius was given to the test device. Consequently, the temperature of the heater then slowly rose up. The responses of the system for both experiments can be seen in Fig. 12. Adding an adaptation law has improved the control performance. From Fig. 12, we can see that the adaptive control contributes to lesser overshoot and faster settling time in system's response. However, this is not the main issue that we want to address in this paper. The main point from the two experiments that we would like to emphasize is that a proxy-based control has strong practicability due to its unique characteristics. In a proxy-based control, we can modify one of the controllers without risking the stability of the whole system. Such a feature is very beneficial during the actual control implementations.

6. CONCLUSION

A proxy-based control is originally proposed within a very specific control framework. The generalization of a proxy-based control is still left unexplored by its authors. Therefore, in this paper, we have explored and generalized the theoretical aspects of a proxy-based control. We have pointed the benefits of having such a control method in real-world control applications, which are not limited to the field of robotics. We have also performed several basic experiments to demonstrate the practicability of a proxy-based control. The demonstration that

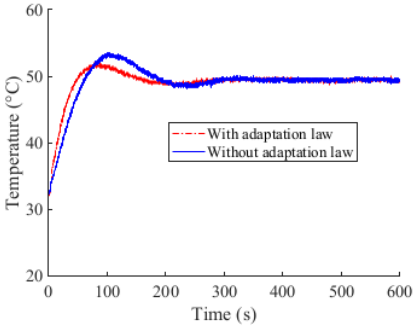

Fig. 12. Step responses of the proposed controllers with and without an adaptation law.

we have done is using a proxy based control with a much simpler structure than the original proxy-based control structure. However, more rigorous theoretical proofs and more sophisticated experiments are still needed. These topics are the future works that we still need to conduct to make this relatively new concept more established.

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