RE-CONFIGURING SLIDING-MODE CONTROLLER FOR A PNEUMATIC SERVO MECHANISM

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Abstract: A self-reconfiguring controller is designed for pneumatic servo mechanisms. For safety critical processes, actuators are important elements of the overall system and may not be desirable to shut down the process when a fault occurs in the actuator. To prevent a system shut-down and proceed even if actuator is faulty, a self-constructing controller is proposed for a pneumatic servo mechanism. The design is developed using a linearised model of servo mechanism. A simple sliding-mode controller implemented in such a way that in case of a fault the controller proceeds with a new gain value to control the servo mechanism.

Keywords: Fault-tolerant control, quantitative and qualitative methods of fault diagnosis, variable structure control, instrumentation systems.

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1. INTRODUCTION

Nowadays, the technology is leading to increasingly complex systems and these complex systems must have the fault accommodation to operate successfully over long periods of time (Rauch, 1994). Re-configurable control is a solution to achieve this goal, it is applied mainly in three situations: (Huzmezan, 1997)

1. to keep the system on track during operation,
2. to increase the performance of the process,
3. to achieve the goal for fault accommodation.

Reconfigurable control is a critical technology (Huzmezan and Maciejowski, 1998, Rauch, 1995) with its objective to detect the fault and recover the functionality of the faulty system as same as that of the nominal system (Yang and Blanke, 2000). Various methods are used for reconfigurable control to cover the requirements of different applications. The behaviour of the reconfigurable control depends upon whether the approach is passive or active. This control idea has been implemented on a variety of military and commercial applications in last two decades to accommodate faults, for example on flight control systems in (Moerder, et.al., 1990, Maybeck and Stevens, 1991, Ochi and Kanai, 1991, Morse and Ossman, 1990) on space technology in (Burke, et.al., 1999, Buckley, 1995) and on unmanned underwater vehicles in (Sullivan, et.al., 1992).

The idea to use variable structure system theory with sliding mode control (Hung, 1993) for reconfiguration purposes stems from the fact that this method alleviates the problems caused by changed system dynamics or parameters. This is the case when a fault occurs in a system component or system itself. Variable structure systems with sliding mode control were first proposed in the 1950’s (Utkin, 1977). However due to the implementation difficulties of high speed switching, it was not until the 1970’s that the approach received the attention it deserved (Ertugrul, 1999). Sliding-mode controllers nowadays enjoy a variety of applications such as in aerospace applications, in process control, in motion control applications and robotics (Young, 1993, Wijesoma, 1990). The main reason for this popularity is the attractive properties that sliding mode controller have, such as applicability to multi input multi output systems, good control performance for nonlinear systems and well established design criteria for discrete time systems. The most significant property of a sliding mode controller is its robustness when uncertainties are inserted into the system.

To the best of my knowledge, studies on variable structure system for reconfigurable control is practically nonexistent prior to our work. It is also stated by Patton in SAFEPROCESS’ 97 that:

“There has been little research in combined robustness design with reconfigurable control and FDI. The challenge is to integrate together the design and implementation of a reconfigurable controlscheme (based upon robust controller designs) and an FDI unit (Patton, 1997).”
The reconfiguring control for fault accommodation purposes is usually achieved by mainly adaptive controllers (Huzmezan, 1997). It can be stated that the proposed novel idea is the first application of variable structure system method as an active reconfiguring controller for fault accommodation.

The aim of this paper is to present some results obtained for the self-reconfiguring sliding-mode control of a linear pneumatic servo mechanism model. The objective of the controller is to control the position of the pneumatic servo mechanism under nominal operation, as well as in case of an abrupt fault occurring in the system. The pneumatics has some non-linearity due to from compressibility of air, friction and stiction. For such non-linear systems, the usual approach is to linearise the system around a nominal position and use this linearised model in the controller design. Recently, there has been many practical implementations of pneumatic servo mechanisms (Lai, et al., 1990; Tang and Walker, 1995; Hamiti, et al., 1996; Ho and Teo; 1999).

The pneumatic system is assumed to be of 2nd order. To have an accurate model, an internal proportional high gain loop is added. The boundary of model uncertainty is calculated with respect to a fault which might occur during the operation. A residual is generated with dedicated observer method to detect the fault. A threshold value is defined by trial-and-error to switch between values of the corrective gain corresponding to nominal and faulty plants. The corrective gain is switched back to the nominal gain when the dedicated observer detects that the system acts nominally.

The aim of proposed method is to avoid chattering for the nominal plant, nevertheless, to keep the process in operation by increasing the robustness of the controller with a larger gain for the faulty plant. It is required to avoid an increase in the controller gain and, hence, in the chattering, for the nominal plant; but for the faulty plant the robustness is a delicate subject to be considered to keep the plant running with an acceptable performance. Here, a trade off appears between the decision of chattering and robustness levels.

2. SERVOMECHANISM DYNAMICS

The servo system consists of 6 main parts: the spool valve and its controller, the cylinder, the load, the system controller and the position feedback potentiometer. (See Fig. 1.) The transfer function for the system can be obtained by combining the governing equations for each system component.

![Figure 1. Pneumatic Servomechanism block diagram.](image-url)
The mathematical equations for each part is derived from the dynamic, energy and flow equations. To have a simplified model the spool position controller is assumed to be proportional. A detailed derivation of these equations is given by Ho and Teo (1999).

3. LINEARIZATION OF THE SERVO MODEL

The equations of a pneumatic servo mechanism form a complicated set of coupled nonlinear differential equations. These nonlinear equations are too complicated for design purposes. Therefore, they need to be linearised and simplified, under the following assumptions:

- Valve spool position is proportional to the input voltage about a desired operating point. Hence, the third order dynamics of valve can be neglected.
- For cylinder ram dynamics, perfect-gas, fast-process, good-insulation, horizontal-orientation assumptions are made.
- For linearisation, it is assumed that changes about a steady-state initial condition is very small and the piston is initially at the central position.

Using all these assumptions, the equations of a pneumatic servo mechanism can be linearised around an equilibrium point. The continuous-time transfer function describing this linearised dynamics of the servo system is then obtained as (Ho and Teo, 1999)

\[ H(s) = \frac{y(s)}{E(s)} = \frac{1100}{s^3 + 181s^2 + 561s} \]  

(1)

where the output \( y \) is the position of the cylinder and the input \( E \) is the valve solenoid voltage.

It is required to have either an acceleration or a pressure feedback for the implementation of sliding mode controller (Pandian, et al., 1997). As the linearised model of the system is of 3\(^{rd}\) order, this is not possible. To facilitate this, an internal feedback loop within the servo system is introduced (Hamiti, et.al.,1996).

Figure 2. Block diagram of the internal loop.
The proportional gain $K$ in Fig. 2 is tuned in such a way that the system is forced to behave like a 2\textsuperscript{nd} order overdamped system. To avoid the effect of this in tracking performance, the largest possible value of $K$ is used, which do not cause overshooting. It is calculated to be $K=0.7$ and with this gain value the closed loop transfer function is obtained as

$$G_c(s) = \frac{y(s)}{w(s)} = \frac{770}{s^3 + 181s^2 + 561s + 770},$$

where $w$ is the input voltage to the inner loop. Closing the loop, a pole is positioned at $s=-177.96$ which can be neglected with respect to the other two poles. Hence, we obtain

$$G_c(s) = \frac{770}{s^2 + 3.13s + 4.33},$$

Further, a feedforward attenuation is required to impose a unity gain, i.e.,

$$G_c(s) = \frac{4.33}{s^2 + 3.13s + 4.33}.$$ 

The self-reconfiguring sliding-mode controller is designed with the 2\textsuperscript{nd} order transfer function in (4).

### 4. CONTROLLER DESIGN

The controller is designed so as to be robust against the model uncertainties and self-reconfiguring if a fault occurs in the system. A sliding-mode control algorithm is used due to its possibility to decouple the high order design problem into lower order independent sub-problems. Also, the robustness property of such a controller is valuable for the systems having model uncertainty and nonlinearity (Drakunov and Utkin, 1992). The control of the pneumatic servo mechanism is achieved by controlling the servo control valve. It is a tracking problem and with respect to the desired response a trajectory has to be followed by the piston of the servo mechanism. The control of the servo mechanism can be achieved by replacing a 2\textsuperscript{nd} order tracking problem by a 1\textsuperscript{st} order stabilisation problem, namely, by keeping the output of the servo mechanism on a pre-defined sliding surface called $s(t)$ (Slotine and Li, 1991).

A single input 2\textsuperscript{nd} order dynamic system can be represented as

$$\ddot{x} = f(x) + b(x)u,$$

where $x$ is the state variable,

$f(x)$ is the unknown dynamics,

$u$ is the control input and

$b(x)$ is the input gain

The bound for the unknown dynamics can be defined as $F$, namely,

$$|\dot{f} - f| \leq F.$$
By using a finite control $u$ the perfect tracking can be achieved only if the initial desired state is such that,

$$ x_d(0) = x(0) $$

(7)

where $x_d$ is the desired output. Considering the tracking error,

$$ \bar{x} = x - x_d, $$

(8)
a time-varying sliding surface $s(t)$ can be defined by the scalar equation $s(x;t)=0$,

$$ s = \dot{x} + \lambda \bar{x} $$

(9)

where $\lambda$ is a strictly positive constant.

Given the initial conditions, perfect tracking $x = x_d$ is equivalent to keeping the states on the sliding surface $s(t)$ for all $t > 0$. This condition, i.e., $s = 0$ represents a linear differential equation with unique solution of $\bar{x} = 0$. Now, the states are driven towards the sliding surface by choosing the control $u$ outside of $s(t)$ so as

$$ -\eta |x| \geq \frac{1}{2} \frac{ds}{dt} s^2, $$

(10)

where $\eta$ is a strictly positive constant (Slotine and Li, 1991).

The differential equation corresponding to (4) can be written as,

$$ \ddot{x}(t) = -3.13\dot{x}(t) - 4.33x(t) + 4.33u(t), $$

(11)

If (9) is differentiated once, we get

$$ \dot{s}(t) = \ddot{x}(t) + \lambda \dot{x}, $$

(12)

By inserting (11) into (12), we obtain

$$ \dot{s}(t) = -3.13\dot{x}(t) - 4.33x(t) + 4.33u(t) - \ddot{x}_d(t) + \lambda \dot{x}, $$

$$ \dot{u}(t) = \frac{1}{4.33} (3.13\dot{x}(t) + 4.33x(t) + \ddot{x}_d(t) - \dot{x}). $$

(13)

This is the equivalent control for the given system to satisfy the condition in (9). To achieve this condition and access the surface despite uncertainty on the dynamics, a corrective control term is added to this equivalent control term, which has discontinuous characteristics. Then, the control turns out to be,

$$ u(t) = \dot{u}(t) - k \text{sgn}(s), $$

(14)

where,

$$ \text{sgn}(s) = \begin{cases} +1 & \text{if } s > 0 \\ -1 & \text{if } s < 0 \end{cases} $$

(15)

The nominal gain $k$ can be defined with the following condition,

$$ k \geq \frac{\dot{b}}{b} F + \left(1 - \frac{\dot{b}}{b}\right) \left| (\ddot{x}_d - 2\lambda \dot{x} - \lambda^2 \ddot{x}) - \dot{b} \right| + \frac{\dot{b}}{b} \eta, $$
By choosing $k$ large enough, the sliding condition is guaranteed.

This gain is implemented as 6 for the nominal plant and 20 for the faulty plant. The fault is simulated by abruptly changing the parameters of the closed-loop system. The residual from a dedicated observer scheme (Clark, et.al., 1975, Clark, 1978) is used to detect a fault in the system. If the residual exceeds a pre-defined threshold, then, the fault will be detected and the sliding-mode controller will then switch the gain to obtain the desired response for the faulty plant.

5. SIMULATION RESULTS

The proposed controller is simulated with Matlab-Simulink Software. The results for nominal and faulty plant cases can be seen together in Figures 3-6. Here a bias fault (Clark, 1978) of 10% created at the 2000th sample and fault detection system detected the fault by a comparison between the residual and predefined threshold value and switched the sliding-mode controller gain. At the 4000th sample, the servo mechanism is forced to act nominally and it is observed that the sliding mode controller gain switched back to the corrective gain which is calculated for the nominal case. Satisfactory tracking is achieved as can be seen from position error values and residual figure.

6. CONCLUSIONS

The basic idea here is to design a controller using sliding-mode methodology, which can yield satisfactory performance when uncertainties inserted into the process at any instant. The robustness against a fault should be adjusted in such a way that the proposed sliding-mode controller should increase the corrective gain when a fault is detected and decrease the gain when the system acts nominally. Hence, the novel idea of this study is a synergic combination of sliding-mode control method and fault detection methods.

The relation between robustness and the size of the controller gain has been illustrated with an example. Here the corrective gain forces the response to the defined sliding surface and equivalent control part tries to keep the response on the sliding surface, in return the stability is achieved asymptotically. It is observed that nominal plants require less corrective gain and causes less chattering. Even any classical control technique such as PID controller could have been used for this part. Nevertheless, it would have failed if a fault develops in the system. On the other hand, a robust sliding-mode controller would cause unnecessary chattering when the system is operating nominally.

By combining a fault detection technique with the standard sliding-mode control approach, it is possible to introduce a high switching gain only when necessary. This idea implemented on a simplified second-order linearised model for a pneumatic servo mechanism. A nontrivial extension of this idea for future research would be the selection of the switching gain vector in the sliding-mode control of a multivariable system.
Such an approach would be useful for military applications especially, when there is no way to stop the process and fix the faulty part such as mine-hunting vehicle autopilot actuators, short-range anti-missile gun actuators, submarine/torpedo steering actuators.

Figure 3. Control input of the plant.

Fig.4. Actual and desired trajectories of the servo mechanism.
Figure 5. Position error of the servo mechanism.

Figure 6. Residual response between DOS and actual system output.

REFERENCES


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