

A New Controller Architecture for High Performance, Robust, and Fault Tolerant Control¹

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Abstract

In this paper, we propose a new feedback controller architecture. The distinguished feature of our new controller architecture is that the controller design for performance and robustness can be done separately which completely overcome the conflict between performance and robustness in the traditional feedback framework. The controller architecture includes two parts: one part for performance and the other part for robustness. The controller architecture works in such a way that the feedback control system will be solely controlled by the performance controller when there is no model uncertainties and external disturbances and the robustification controller will only be active when there is model uncertainties or external disturbances.

1 Introduction

A fundamental reason for using feedback control is to achieve desired performance in the presence of external disturbances and model uncertainties. It is well known that there is an intrinsic conflict between performance and robustness in the standard feedback framework, see [3, 9, 11, 19, 20] for some detailed analyses and discussions. In other words, one must make a tradeoff between achievable performance and robustness against external disturbances and model uncertainties. For example, a high performance controller designed for a nominal model may have very little robustness against the model uncertainties and external disturbances. For this reason, worst-case robust control design techniques such as H_∞ control, L_1 control, μ synthesis, etc, have gained popularity in the last twenty years or so, see for example, [1, 2, 6, 8, 13, 17, 19, 20] and references therein. Unfortunately, it is well

recognized in the robust control community that a robust controller design is usually achieved at the expense of performance. This is not hard to understand since most robust control design techniques are based on the worst possible scenario which may never occur in a particular control system.

In this paper, we shall propose a new controller architecture that can completely overcome the conflict between performance and robustness in the traditional feedback framework. This controller architecture uses the well-known Youla controller parameterization in a completely different way. The distinguished feature of our new controller architecture is that the controller design for performance and robustness can be done separately. First of all, a high performance controller, say K_0 , can be designed using any method, and then a robustification controller, say Q , can be designed to guarantee robust stability and robust performance using any standard robust control techniques. The feedback control system will be solely controlled by the high performance controller K_0 when there is no model uncertainties and external disturbances while the robustification controller Q will only be active when there are model uncertainties or external disturbances.

The paper is organized as follows. Section 2 introduces the Youla controller parameterization. We propose the new controller architecture in Section 3. In Section 4, we show how our controller architecture can be used to design high performance and fault tolerant controllers. Section 5 discusses how to design the robustification controllers in this new controller framework. Section 6 makes the connection between this new controller architecture and the two degree of freedom controller structure. Section 7 considers an dual version of this new controller architecture and makes some connections with the well known Internal Model Control (IMC) structure. Some concluding remarks are given in Section 8.

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2 Preliminary

Consider a standard feedback configuration shown in Figure 1 where P is a linear time invariant plant and K is a linear time invariant controller. We shall assume without loss of generality that the feedback system is well-posed, i.e., $\det(I - P(\infty)K(\infty)) \neq 0$.

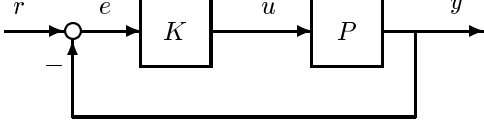


Figure 1: Standard Feedback Configuration

The following lemma is a simple variation of the well-known Youla controller parameterization [17, 19, 20] and will play the key role to our development in this paper.

Lemma 1 *Suppose that K_0 stabilizes internally the feedback system shown in Figure 1. Let K_0 and P have the following right and left coprime factorizations*

$$K_0 = UV^{-1} = \tilde{V}^{-1}\tilde{U}, \quad P = NM^{-1} = \tilde{M}^{-1}\tilde{N}.$$

Then every controller K that internally stabilizes the feedback system shown in Figure 1 can be written in the following form:

$$K = (\tilde{V} - Q\tilde{N})^{-1}(\tilde{U} + Q\tilde{M})$$

for some $Q \in H_\infty$ such that $\det(\tilde{V}(\infty) - Q(\infty)\tilde{N}(\infty)) \neq 0$, or, equivalently,

$$K = (U + MQ)(V - NQ)^{-1}$$

for some $Q \in H_\infty$ such that $\det(V(\infty) - N(\infty)Q(\infty)) \neq 0$.

It is noted that in the standard Youla controller parameterization, \tilde{U} , \tilde{V} , \tilde{U} and \tilde{V} are chosen so that $\tilde{U}\tilde{N} + \tilde{V}\tilde{M} = I$ and $\tilde{N}\tilde{U} + \tilde{M}\tilde{V} = I$, in particular, K_0 is chosen to be an observer based stabilizing controller. Unfortunately, this choice of K_0 is not always desirable in our subsequent development. The controller parameterizations in the above lemma do not impose such constraints. In fact, we shall always choose K_0 as our nominal controller that satisfies our nominal design objectives. In particular, K_0 can be a simple PID controller.

Note that the feedback system with a controller

$$K = (\tilde{V} - Q\tilde{N})^{-1}(\tilde{U} + Q\tilde{M})$$

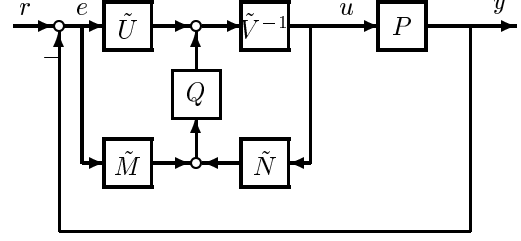


Figure 2: Youla Controller Parameterization

can be implemented either as shown in Figure 1 after obtaining a total transfer function K or as shown in Figure 2 with five blocks. For a fixed Q , it is clear that there is no advantage in using the implementation in Figure 2 and, in fact, this implementation is usually not desirable since it needs much higher order controller implementation. It does have some advantages when Q is made to be adaptive, see [14]. We shall not discuss this issue further.

3 A New Controller Architecture

It is well understood that the model P is in general not perfectly known. What one actually knows is a nominal model P_0 . Now assume that K_0 is a stabilizing controller for the nominal plant P_0 and assume P_0 and K_0 have the following coprime factorizations

$$K_0 = UV^{-1} = \tilde{V}^{-1}\tilde{U}, \quad P_0 = NM^{-1} = \tilde{M}^{-1}\tilde{N}.$$

Then by Lemma 1, every stabilizing controller for P_0 can be written in the following form:

$$K = (\tilde{V} - Q\tilde{N})^{-1}(\tilde{U} + Q\tilde{M})$$

for some $Q \in H_\infty$ such that $\det(\tilde{V}(\infty) - Q(\infty)\tilde{N}(\infty)) \neq 0$, or, equivalently,

$$K = (U + MQ)(V - NQ)^{-1}$$

for some $Q \in H_\infty$ such that $\det(V(\infty) - N(\infty)Q(\infty)) \neq 0$.

We shall now propose a new way of implementing the controller

$$K = (\tilde{V} - Q\tilde{N})^{-1}(\tilde{U} + Q\tilde{M})$$

as shown in Figure 3. Note that the feedback diagram in Figure 3 is not equivalent to the diagram in Figure 2 since the reference signal r enters into the system from a different location. Nevertheless, the internal stability of the system is not changed since the transfer function from y to u is not changed.

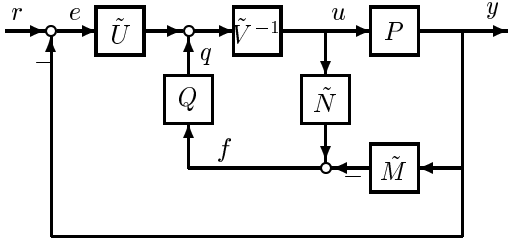


Figure 3: Generalized Internal Model Control Structure

Due to the similarity with the well-known Internal Model Control (IMC), see [13] for details, we shall call our controller framework as *Generalized Internal Model Control (GIMC)*. We shall see later on their connections and the advantages of our new GIMC over the traditional IMC. It is quite clear that the controller implementation shown in Figure 3 also stabilizes internally the feedback system with plant P_0 for any $Q \in H_\infty$ such that $\det(\tilde{V}(\infty) - Q(\infty)\tilde{N}(\infty)) \neq 0$.

The distinguished feature of this controller implementation is that the inner loop feedback signal f is always zero, i.e., $f = 0$, if the plant model is perfect, i.e., if $P = P_0$. The inner loop is only active when there is a model uncertainty or other sources of uncertainties such as disturbances and sensor noises. Thus Q can be designed to robustify the feedback systems. Thus our new controller design architecture has a clear separation between performance and robustness.

Controller Design: A high performance robust system can be designed in two steps: (a) Design $K_0 = \tilde{V}^{-1}\tilde{U}$ to satisfy the system performance specifications with a nominal plant model P_0 ; (b) Design Q to satisfy the system robustness requirements. Note that the controller Q will not affect the system nominal performance.

It should be emphasized that K_0 is not just any stabilizing controller as in most of controller parameterizations used in the literature, it is designed to satisfy certain performance specifications. For example, K_0 may be a simple PI controller $K_0(s) = \frac{K_p(s+a)}{s}$ that satisfies our design specifications, in which case we can take $\tilde{U} = 1$ and $\tilde{V}^{-1} = K_0$.

Suppose that P_0 has the following state space realization

$$P_0 = \left[\begin{array}{c|c} A & B \\ \hline C & D \end{array} \right]$$

and assume that (A, B) is stabilizable and (C, A) is detectable. Let F and L be such that $A + BF$ and $A + LC$ are stable. Then the left coprime factorization $P_0 = \tilde{M}^{-1}\tilde{N}$ can be chosen as

$$\left[\begin{array}{c|c} \tilde{N} & \tilde{M} \end{array} \right] = \left[\begin{array}{c|c|c} A + LC & B + LD & L \\ \hline C & D & I \end{array} \right].$$

Denote the state vector of $\left[\begin{array}{c|c} \tilde{N} & \tilde{M} \end{array} \right]$ by \hat{x} and note that

$$f = \tilde{N}u - \tilde{M}y.$$

Then we have

$$\begin{aligned} \dot{\hat{x}} &= (A + LC)\hat{x} + (B + LD)u - Ly \\ f &= (C\hat{x} + Du) - y \end{aligned}$$

i.e., f is the estimated output error.

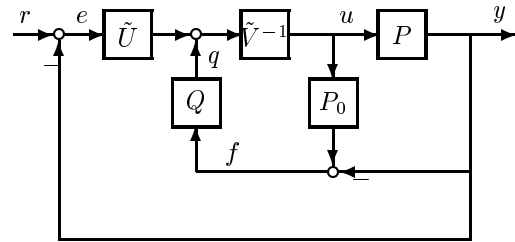


Figure 4: GIMC with Stable Plant

When the plant itself is stable, we can take

$$\tilde{N} = P_0, \quad \tilde{M} = I.$$

Then the feedback system shown in Figure 3 becomes Figure 4. It is clear from this diagram that f is the error between the output of the nominal model and the output of the true system.

4 Application to Fault Tolerant Control

Surprisingly, the estimated output error f defined in Figure 3 is in fact the *residual signal* used in fault diagnosis literature [4, 5, 7]. ($q = Qf$ is also considered in the fault diagnosis literature as a residual signal but the motivation for the choice of Q is quite different from here.) In the fault diagnosis literature, f is used to detect the possible faults in actuators and/or sensors. Unfortunately, only a very few published papers have dealt with how to use the residual signal to design fault tolerant controllers, see [4, 15] and references therein. The existing approaches to the design of fault tolerant controllers are mostly based on robust control techniques. More precisely, a single controller is usually designed using robust control methods by assuming the possible actuators and/or sensors failures as

model uncertainties. For example, a possible actuator fault in the first channel of an m actuator system with $B = [B_1, B_2, \dots, B_m]$ can be represented by introducing an uncertainty in the corresponding input matrix

$$\dot{x} = Ax + B_1(1+\delta)u_1 + B_2u_2 + \dots + B_mu_m, \quad \delta \in [-1, 0]$$

where $\delta = -1$ implies a total failure of the actuator and $\delta = 0$ implies no actuator failure. Then a robust controller is designed for this uncertain system and the resulting controller is implemented using the standard feedback structure shown in Figure 1. This is clearly the worst case design and it is not surprising to see that such fault tolerant feedback system may perform very poorly compared with a non-fault-tolerant control system when there is no actuator and/or sensor failure. On the other hand, our GIMC structure gives all possible fault tolerant controllers. Our fault tolerant controllers can be designed such that they provide adequate performance when there are no faults in the systems and as much tolerance as possible by any other fault tolerant or robust controllers. Such controllers can be designed in two steps:

- (a) Design $K_0 = \tilde{V}^{-1}\tilde{U}$ to satisfy the system performance by assuming no faults (and model uncertainties).
- (b) Design Q to tolerate possible actuators and/or sensors failures (and model uncertainties). This Q can be designed using standard robust control techniques, fuzzy control methods, adaptive control techniques, etc.

Note that it is shown in [12] that all nonlinear and time varying stabilizing controllers for a linear time invariant and strictly proper plant P_0 , i.e., $P_0(\infty) = 0$, can also be parameterized as

$$K = (\tilde{V} - Q\tilde{N})^{-1}(\tilde{U} + Q\tilde{M})$$

as long as Q is allowed to be any nonlinear and time varying stable system. Thus the system stability is guaranteed as long as Q is chosen to be a stable nonlinear and time varying system. Hence we can choose a fixed Q or a nonlinear and time varying Q . One can also design a Q for each failure mode, then switch among the Q 's when a certain failure mode is detected from the residual signal f . This is shown schematically in Figure 5.

It is also easy to see that Q can also be used as a redundant reliable controller in a reliable control system. We should expect a reliable controller designed using this framework can performance much

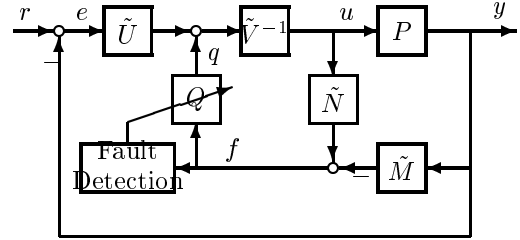


Figure 5: A Fault Tolerant Control Scheme

better than conventional design methods based on robust control techniques such as the Riccati equation method proposed in [16].

It is not hard to see that our generalized internal model control can also be made to be adaptive or used for gain scheduling control. One way to design an adaptive robust control law is to devise a mechanism to adjust the free stable controller Q online. Switching among several predefined controllers may also be used. We should expect that this adaptive robust control scheme will perform better than the conventional adaptive robust control scheme if the nominal performance controller $K_0 = \tilde{V}^{-1}\tilde{U}$ is suitable designed.

5 Robustification

In this section, we shall consider how to design the controller Q for robustness. In general, we can assume without loss of generality that the uncertain system can be described by a linear fractional transformation as shown in Figure 6 where Δ includes all model uncertainties and are generally in block diagonal form, d includes all disturbances and sensor noises, and z includes all signals to be controlled such as the weighted control signal and weighted output signal. Then the problem can be put in a general linear fractional transformation form as shown in Figure 7 and Q can be designed using standard robust control techniques, see [1, 19, 20] for details.

We should point out that, as long as r and e are not involved directly in the design of Q (i.e., it does not shown in Figure 8), our controller implementation should in principle perform no worse than the standard robust controller implementation does with regard to the robustness and the performance of the controlled signal z since the transfer function from y to u , the standard robust controller, is always the same and is independent of the nominal controller K_0 . In the worst case (i.e., when the uncertainties are in the worst case), our controller implementa-

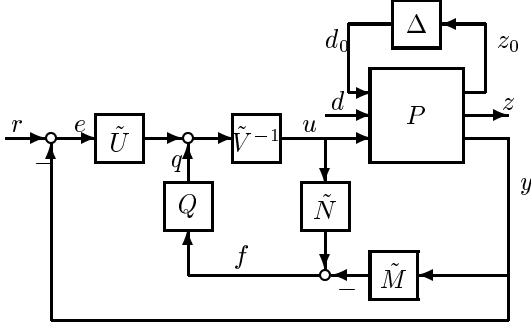


Figure 6: GIMC with General Uncertain Plant

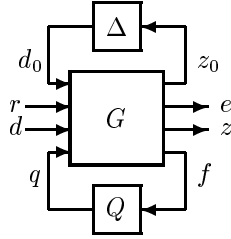


Figure 7: General Linear Fractional Transformation Form

tion will be equivalent to the existing robust control design. Of course, if there is no uncertainty, our controller will performance as well as a nominal controller does. In fact, our framework provides a great flexibility in controller design, for example, one could still use all the robust and H_∞ design techniques here. All one has to do is to start with a good performance controller and then everything can proceed as in the standard robust control design procedure to find the robust controller Q . The only difference is that we are not interested in plugging Q into the controller parameterization to find the total controller rather we will implement the performance controller and the robust controller Q separately.

6 Connections with Two Degree of Freedom Controllers

It turns out that our GIMC structure is closely related to the two degree of freedom control strategy proposed in the literature, see [17] and references therein. Consider a two degree of freedom feedback system shown in Figure 8.

It is shown in [17] that all two degree of freedom controllers can be parameterized as

$$\begin{bmatrix} K_1 & K_2 \end{bmatrix} = (\tilde{V} - Q\tilde{N})^{-1} \begin{bmatrix} R & \tilde{U} + Q\tilde{M} \end{bmatrix}$$

where $Q \in H_\infty$ and $R \in H_\infty$ are any systems such

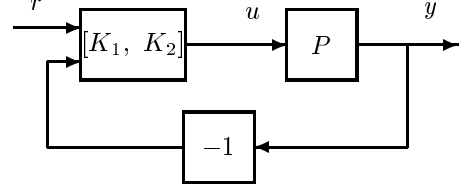


Figure 8: Two Degree of Freedom Controller

that $\det(\tilde{V}(\infty) - Q(\infty)\tilde{N}(\infty)) \neq 0$.

Now take $R = \tilde{U}\tilde{R}$ for any $\tilde{R} \in H_\infty$. Then the two degree of freedom controller can be implemented as shown in Figure 9, which is in fact a general form of our GIMC. Of course, the conventional 2DOF controllers are not implemented in this fashion. Nevertheless, we believe this is probably a more suitable alternative implementation if the computational demand due to the high order controllers can be managed.

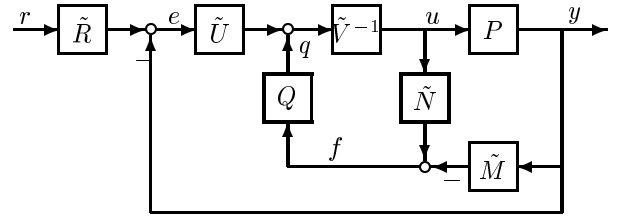


Figure 9: A GIMC Implementation of Two Degree of Freedom Controller

7 Dual Structure

A dual GIMC structure can be obtained by using the right coprime factorization approach as shown in Figure 10. This dual structure was actually first proposed in one of the author's book [18] (Page 78).

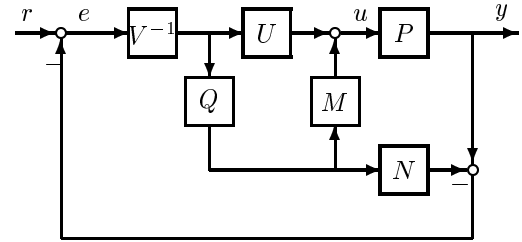


Figure 10: Generalized Internal Model Control Using Right Coprime Factorization

However, we believe this GIMC structure is less favorable comparing with the GIMC structure using left coprime factorization. One reason is that Q is always active even with a perfect model. Since the

output of M adds additional signal to the actuator, it may saturate the actuator easily even though the net effect of this Q controller in the ideal case is cancelled in the feedback loop. Another reason is that it is not clear how this structure can be used for fault tolerant control. Nevertheless, this approach is closely related to the well-known IMC structure. Indeed, if P_0 is stable, then we can pick $M = I$ and $N = P_0$. Since $K_0 = 0$ is a stabilizing controller, one can also choose $U = 0$ and $V = I$. Then feedback system shown in Figure 10 is exactly the well-known IMC system as shown in Figure 11. The design of such Q is discussed in detail in [13].

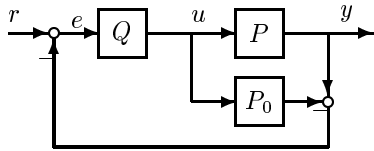


Figure 11: Standard IMC Structure

8 Conclusions

In this paper, we have proposed a new controller architecture that we expect to have significant impact on modern control system design. A distinguished feature of this new architecture is that the design for tracking performance and robustness can be structurally separated. This controller architecture offers a new vision for robust control, fault tolerant control, adaptive robust control, etc.

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