Chapter 11
Control Architectures

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11.1 Introduction

Distributed control systems can be of various forms as described in Chap. 10. For control of such systems, one also needs a variety of control structures. Engineering experiences illustrate that a wide variety of control architectures are useful. A classification of control structures is provided below.

A control architecture is the description of the various controllers of a distributed or multilevel control system and the ways in which these controllers are functioning. An example is the control architecture of a communication network where there is a controller at every node and, for example, a controller for the full network. Another example is that controllers of a set of underwater vehicles with one controller per vehicle and a coordinating controller at the surface vessel. To distinguish a distributed system as a system without inputs from a control system with inputs, the term distributed control system will be used. A multilevel control system is then defined correspondingly. The various controllers can be operating synchronously or asynchronously, there are examples of both cases in the literature.

For control design and control synthesis, the control engineer has to make a choice of the control architecture. Often the choice is based on the system architecture of the system under consideration, see Chap. 10 for a description of system architectures. The main choices of the control engineer are whether or not there is only one central controller or a set of controllers. If the choice is for a set of controllers, then the second choice is whether the various controllers should communicate directly by message passing. In a multilevel control architecture, the specification includes how the controllers of various levels communicate and when. The closed-loop system then is a composition of all controllers with all subsystems of the control system.

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11.2 Classification

In the literature of control theory, there is no standard for classification of control architectures. Therefore, one is introduced below. It should be clear that the classification proposed in this chapter is tentative, it may have to be modified later on. Yet, for the purpose of this book, it is better to have a preliminary classification than not to have one. The distinctions between the classification categories are not yet as deep as one would like. This classification was first published in [7].

The main guideline used by the author for the classification of control architectures is the distinction for distributed and for multilevel control systems in terms of the degree of coordination of the subsystems and of the complexity of the levels of a multilevel system. The coordination can be regarded as a restriction on the behavior of the other subsystems. A complexity concept of multilevel control systems is not yet formulated. In Chap. 44, this is stated as an important open research issue.

The classification consists of the following subclasses:

- Centralized control.
- Distributed control.
- Distributed control with direct communication between controllers.
- Coordinated control.
- Multilevel control.

Below, these subclasses are described. Afterward, a comparison is made of the control architectures and principles are formulated for choosing one of these. The control objectives need not depend on the control architecture chosen. However, if a control architecture has been chosen, then the overall control objective has to subdivided over the various control subsystems. In addition, then the control synthesis has to be carried out either centrally or in a decentralized or distributed way. The control synthesis of each of the control architectures is described in the subsequent parts of the book.

11.3 Central Control Architecture

In this case, there is one controller which controls the complete distributed system. An engineering example is the controller of a printer, see Chap. 8. The advantages of the central control architecture is the simplicity of control synthesis. The main disadvantage is the complexity of control synthesis, the communication efforts required, and the lack of robustness in case of failures. The centralized control architecture is not described further because it is treated in every textbook of control engineering.

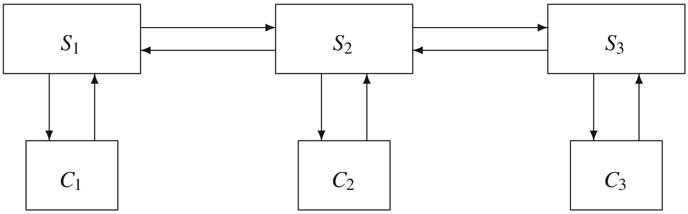

Fig. 11.1 Diagram of the distributed control architecture of an example of a distributed system. The subsystems are indicated by S_i and the corresponding controllers by C_i

11.4 Distributed Control

In the subclass of distributed control architectures, there are two or more control laws or controllers. Each controller receives an observation stream directly from the associated subsystem and produces an input to the distributed subsystem, see in Fig. 11.1, the arrows from one of the S_i boxes to the corresponding C_i boxes and back. There is no direct communication whatsoever between different controllers. See Fig. 11.1 for a diagram of the control architecture of distributed control. An example of this control architecture is the control of a large-scale power system if there is no communication between the controllers at various subnetworks.

Control synthesis of distributed control is difficult. Consider a cost function of the tuple of control laws. The problem is to determine a tuple of control laws which achieves the lowest cost. Information about distributed control may be found in the chapters on team theory, see Chaps. 18 and 19.

11.5 Distributed Control with Direct Communication Between Controllers

In the subclass of control architectures of distributed control with direct communication between controllers, there are two or more control laws or controllers. Each controller receives an observation stream directly from the distributed system and also receives one or more observation streams directly from other controllers. The observation streams from other controllers need not arrive at every time step, meaning the information is not sent after every observation or it is a strict subset of the state information. The diagram of this control architecture is displayed in Fig. 11.2.

There always exists indirect communication between controllers via the control system. With direct communication is meant the direct communication link between controllers, see the arrows between C_1 and C_2 in Fig. 11.2.

Distributed control with communication is a control architecture used for many control engineering problems. The alternating bit protocol of communication networks is a particular example of this control architecture which has been analyzed

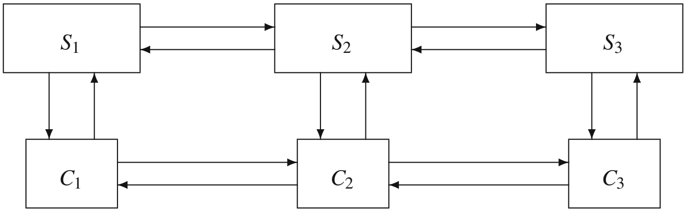

Fig. 11.2 Diagram of the control architecture of distributed control with communication of an example of a distributed system in which additional direct links between the subsystems S_1 and S_3, and C_1 and C_3 are not indicated in the figure. The solid lines between the C_i boxes indicate that the communication takes place every time step

as a problem of a discrete-event system. In this case, there is communication from the receiver to the sender. The backpressure algorithm for the routing of messages in a communication network is another example, see Chap. 30. Another example is a platoon of cars on a motorway in which each car only communicates with its nearest neighbors, the car directly in front and the car directly behind. It has been proven that this control architecture cannot stabilize the platoon, see Chap. 22. The communication requires financial resources and energy. But those costs seem to be less than the loss in performance if no communication is used. That communication between controllers is also an economic issue was already remarked by J. Marschak and R. Radner.

Control synthesis of distributed control with communication is even more difficult than distributed control without communication. First, a communication law has to be determined when extra observations are to be requested or are to be sent. Next the additional observations have to be integrated into a state estimator. Finally, a tuple of control laws has to be determined. Because of these difficulties, there is no substantial theory for this case, except of the case of distributed control with communication of discrete-event systems. Yet, in practice, researchers formulate control laws of which the performance is satisfactory as in the alternating bit protocol.

11.6 Coordinated Control

In the subclass of coordinated control architectures, one considers a coordinated system and a corresponding coordinated control architecture. It applies only to a coordinated system as defined in Chap. 10. Recall from Chap. 10 that a coordinated system consists of a coordinator and two or more subsystems such that conditioned on the coordinator the subsystems are independent. In a coordinated control architecture, there is a controller for the coordinator and a controller for each of the subsystems. The controller influences the subsystems while the subsystems do not influence the coordinator. In the Chapter System Architectures, it is described that the task of a

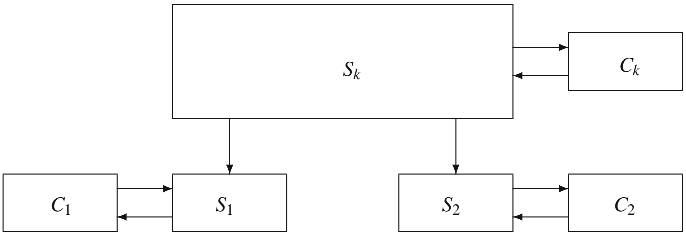

Fig. 11.3 Diagram of the control architecture of coordinated control of an example of a coordinated system in which S_k denotes the coordinator, S_1 and S_2 denote the subsystems, and the various controllers are indicated by the symbol C_i

coordinator is to restrict the behavior of the two subsystems often inspired by control objectives or other properties.

See Fig. 11.3 for the diagram of this control architecture.

An example of coordination control is where a surface vessel ship coordinates the actions of two underwater vehicles.

Coordination control becomes of interest when the control objectives cannot be met by distributed control with or without communication. It is then necessary to impose a degree of centralized control here called coordination control. An example is coordination control of coordinated discrete-event system where, without coordinator, blocking occurs meaning the distributed system does not function as needed. In a coordinated system, there is communication from the coordinator to the subsystems.

There is also the class of M systems, see Chap. 10, in which the control architecture is almost the same as that of a coordination control architecture except that the coordinator and each of the subsystems communicate in both directions.

Control synthesis of a distributed control system with the coordination control architecture is a little involved. Please have a look at the corresponding chapters in this collection, the Chaps. 10, 28, and 29.

11.7 Multilevel Control

In this subclass of control architectures, one considers a multilevel control system and a corresponding multilevel control architecture. Recall from Chap. 10 that a multilevel control system, see Fig. 11.4 consists of two or more levels in which each subsystem of a level is related to one or more subsystems at the next-lower level and related to one subsystem at the next-higher level. In a multilevel control architecture, there is one control law or controller per subsystem. Thus, a controller of one subsystem is connected to those controllers of subsystems at the next-lower level to which the subsystem is related and it is connected to the controller of the subsystem at the next-higher level to which the subsystem is related. A multilevel control architecture

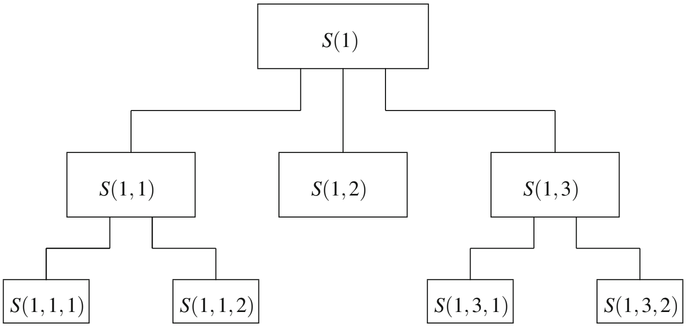

Fig. 11.4 Diagram of the control architecture of multilevel control of an example multilevel control system. A *box* represents a closed-loop system consisting of a subsystem and its controller so as not to make the figure too complicated. A link between two boxes is always a two-directional physical or communication channel. Controllers of subsystems which are linked to the same parent subsystem could have a communication link between them not indicated in the figure

is a generalization of the coordination control architecture defined above or of the M-system control architecture.

A technological example of a multilevel control architecture is a telephone network. There is a controller at every level and at the highest level a controller for the computation of the routing tables. The multilevel structure proposed for computer networks in the book by A. Tannenbaum is another example. The protocols for locating a subscriber in mobile communication networks is another example. Multilevel systems have been used in the society of the Aztecs and for the organization of the Roman army.

Multilevel control for particular systems has been investigated. For discrete-event systems, multilevel control has been investigated but it seems to concern mostly the case of one subsystem at each level. More theory is needed for multilevel control.

11.8 Comparison and Choice Principles

The control architectures defined above are listed in the order of increasing degree of dependence between the controllers. It is possible to consider other orders on the set of subsystems. Below a multilevel system is regarded as a special case of a distributed system which can be obtained by ignoring the structure of the multilevel system.

Problem 11.1 Formulate guidelines for the selection of a control architecture for any particular distributed control system.

Preliminary guidelines follow.

1. Use the distributed control architecture as much as possible at the subsystem level. This approach requires the least restriction on the behaviors of the subsystems. See Part IV of this book for the relevant chapters.

2. If the closed-loop system with the distributed control architecture cannot meet the control objectives, then consider the architecture of distributed control with direct communication between controllers. The nearest-neighbor control architecture may be explored first. See Part V of this book for the relevant chapters.
3. If the performance with respect to the control objectives is still unsatisfactory, then the guideline is to use the coordination control architecture. The particular level of satisfaction of the control objectives has to be set in each individual case. See Part III if this book on coordination control for the corresponding control synthesis method.
4. If the complexity of the distributed control system is very large, then a multilevel system with the multilevel control architecture seems best. See Part VI of this book for chapters on this topic.

Needed is a complexity theory for multilevel control systems. No such theory is currently available. Chapter 44 formulates the formulation of a complexity of multilevel systems as an important research issue. The last step of the guideline depends on such a complexity theory.

11.9 Further Reading

A reader novel to the subject is advised to read the book [5] or the papers [7, 8].

Books on control of decentralized systems include [2, 3, 6, 9]. Books on multilevel systems include [1, 4].

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