Chapter 11
Metamorphic Systems: A Schema for Adaptive Autonomous Systems

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11.1 Introduction

Unmanned vehicles (UVs) are taking on increasing roles in military and space missions. These UVs operate in radically different domains, yet they have several common features: (1) they must survive in harsh domains for extended time periods, (2) they must adapt their behaviour to accommodate changing circumstances and (3) they must operate autonomously, which means they must perform assigned tasks with little or no human intervention. For instance, since August 2012 NASA's scientific laboratory rover Curiosity has been exploring the Martian surface searching for signs of life (NASA, 2012). Martian surface temperatures average $-63\,^{\circ}$C. As another example, the U.S. Navy is currently developing the Anti-submarine Continuous Trail Unmanned Vessel (ACTUV) to track quiet diesel-electric submarines. The goal is to have a UV that can autonomously interact with an intelligent adversary over ranges spanning thousands of kilometers while enduring harsh ocean environmental conditions for months at a time (DARPA, 2012).

UVs are a classic example of a system that must be both adaptive and autonomous. Unfortunately, autonomous operation is particularly difficult to build into systems. Being autonomous means the system must be aware, responsive and reconfigurable. It must be aware of its domain (physical environment) to see whether its current behaviour matches mission assignments. It must determine new, more appropriate behaviours to respond to changing domain conditions or loss in performance due to faults. It must reconfigure software modules and/or hardware components as needed to acquire a different behaviour consistent with mission requirements.

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Obviously these types of systems require a non-conventional design philosophy because traditional design methods simply aren't equipped to handle the unique requirements of autonomous systems. Recently Greenwood and Tyrrell proposed the *metamorphic system*, which serves as a general model for designing adaptive autonomous systems (Greenwood and Tyrrell, 2010). The metamorphic system is reconfigurable, with different design alternatives that exhibit different behaviour in different domains. These systems can detect when the current system behaviour deviates from a desired behaviour. They can even evaluate long-term behaviour and initiate new behaviour before the system performance deteriorates too much. All of these tasks can be done autonomously. Moreover, the metamorphic system concept can be applied to electrical, mechanical, chemical, biological or any combination of these types of systems.

Perhaps the most desirable feature of metamorphic systems is their ability to react to immediate behaviour deviations or preempt gradually deteriorating behaviour. These features will be the primary focus of this chapter. A DC motor with varying loads (representing different physical domains) is presented as a test problem to highlight features and mechanisms inherent in metamorphic systems. The objective is to maintain a desired step response regardless of the load. We will illustrate how deteriorating behaviour can be predicted using *event-processing* techniques. We will also show how new configurations can be instantiated quickly enough to accommodate any real-time reconfiguration requirements.

The rest of the chapter is organised as follows. Section 11.2 describes the metamorphic system concept. The discussion is abstract to make the key ideas clear without getting bogged down in specific implementation details. Section 11.3 discusses the basic concepts of event-processing. This form of processing is particularly suitable for analysing long-term behavioural trends while minimising computational effort and reducing power consumption. The discussion is general enough to serve as a brief tutorial on the topic. A DC motor problem is introduced in Section 11.4. This motor problem provides a framework to illustrate the key features of a metamorphic system. As stated above, the focus of the chapter will be on the assessment module and the detection mechanism in metamorphic systems. Section 11.5 shows how these components can provide autonomous and adaptive behaviour in the DC motor problem. Some implementation approaches are also discussed. Finally, Section 11.6 summarises the key ideas.

11.2 Metamorphic Systems

A block diagram of the metamorphic system is shown in Figure 11.1. The substrate contains pre-designed configurations of a given system. Each configuration is fully functional. Duplicates are not allowed. The reason various configurations are provided is to get alternative behaviour in different physical domains; these different configurations are what produces adaptive behaviour. (Of course, their behaviour must completely satisfy all specifications within those different physical domains.)