Data — The Forgotten System Component?

by Neil Storey, Coventry, U.K., and Alastair Faulkner, Flixborough, U.K.

The increasing use of COTS components is leading to the production of a large number of systems that use standardized hardware and software customized for a particular situation by the use of data. Where such systems are used in safety-related applications, the safety of the resulting system will often be dependent on the correctness of this data. It is therefore essential that this data component is developed and tested to the same level of rigor as other system elements.

> *"…anecdotal evidence suggests that data does not receive the same attention as other system elements…"*

Despite the obvious importance of data correctness in safety-related systems, anecdotal evidence suggests that data does not receive the same attention as other system elements. This view is reinforced by the observation that the standards in this area say almost nothing about the design, production, verification or maintenance of data.

This article describes a study to investigate the techniques being used to produce and manage data in a range of safety-related industries.

Introduction

Over the last decade, we have seen an increasing reliance on computers in all forms of safety-related system. Because of the high development costs associated with such systems, developers have moved toward the use of standardized hardware and software, wherever possible. This, in turn, has led to the large-scale use of COTS products, and to the development of systems that can be easily adapted to a range of similar situations [Ref. 1]. Often these systems are not only data-driven but also data-intensive. In such cases, a large and significant component of each project is data, which may represent a substantial part of the complexity and the cost of the complete system.

Since safety is a property of a complete system, rather than its individual components, it follows that attention must be paid to *all* its components during the development process. Over the years, a great many techniques have been developed for treating the hardware and software elements of computer systems, but less attention has been directed at the data element. This is evident from the various standards and guidelines relating to safety-related systems. Generic standards, such as IEC 61508 [Ref. 2], provide extensive guidance on hardware and software issues, and are used across a range of industrial sectors. However, these say almost nothing about the generation, testing or control of data. Similarly, industry-specific standards in the civil aircraft, military, nuclear and railway sectors [Refs. 3-6] give little guidance in this area.

Perhaps one of the reasons is that these documents make the tacit assumption that data is simply part of software and is therefore covered by the general guidance given. Certainly, many definitions of software include data (and documentation) within its remit. However, it is quite clear that in many cases the data component is not developed alongside more conventional software, and is not developed with the same degree of care.

To see how and why data is treated differently from software, we need to look at the nature of data within computer-based systems. Here we are primarily interested in systems that make use of large amounts of data. We will refer to such systems as data-driven systems.

Data in Data-Driven Systems

All computer programs make use of data in one form or another. Most programs will contain constants that are used within their operation, and will calculate values as they are executed. Temporary, or intermediate, values may be stored in specific memory locations or on a stack. Many systems also make use of calibration constants or device characteristics for particular elements. All these can be thought of as either constant or variable data that forms an integral part of the software.

This article is *not* concerned with data that forms an integral part of the software. Here we are concerned with the use of large quantities of data by a safety-related system. This data might, for example, describe the changing environment in which a system is to operate, or perhaps be used to configure a system for a particular application. Such data is often generated quite independently from the "executable" software.

In many data-driven systems, some form of application software implements a series of required functions that are then applied to a set of data. The application software may be a COTS program, or some custom or semi-custom software. The data on which it acts often represents some aspect of the physical world. For example, the application data could be a railway control system, and in this case the data would represent (among other things) the physical layout of the tracks and the instantaneous positions of the trains. In this example, the data is used to configure the system for this particular situation. The same suite of software applications could be used with different data to control a different railway network in another location. Other examples of data-driven systems include those used in Air Traffic Control (ATC). Here, commercial ATC packages are configured to work within a particular air space by the use of data. This data will include a fixed description of the area (including an altitude map of the region and the location of airfields, etc.) and transient data on the positions of aircraft in the region at any time.

In these examples, and in many data-driven systems, the application software is often developed and supplied together with the hardware of the system. This software may well be a standard product that has been developed and refined over a number of years. However, the configuration data is invariably a unique

References for this article are found on page 36.

set of data that is developed quite independently.

Data Development

While the configuration data is often developed separately from the application software, it is clearly an essential part of the complete system. Consequently, the correctness of this data will normally be closely linked to overall system safety. This being the case, it is likely that the safety integrity requirements of the configuration software will be comparable to those of the application software.

In any safety-related application, the development methods used must reflect the safety integrity level (SIL) of the system. If the SIL of the configuration data is the same as that of the application software, then one would expect that each would be developed and verified with a similar amount of care and rigor. However, there is much anecdotal evidence to suggest that this is not the case.

A possible reason why data might be treated differently from software is that very little guidance is available on appropriate data development methods. Within most standards and guidelines, data is considered to be an integral part of software. However, while these documents give a great deal of attention to the executable aspects of software, they give little attention to the special requirements of data.

As an example, if we look at IEC 61508, we find that a complete section of the standard relates to software. The section contains a subclause entitled "General Requirements," which sets out a range of requirements for the software of the system. This section ends with the statement, "This subclause … shall, in so far as it is appropriate, apply to data including any data generation languages." This statement perhaps sums up the treatment of data within the standard. Data is seen as an integral part of the software, having few special characteristics or special requirements.

It would be unfair to suggest that IEC 61508 says nothing about the requirements of data. For example, it says at one point that "…the design method chosen shall possess features that facilitate … the expression of … data structures and their properties." However, the standard says nothing of the methods that should be used to generate or verify data, and it does not identify specific data requirements.

A Data Development Life Cycle

The authors of this article would argue that since data in data-driven systems is often developed separately from other parts of the system, it should be treated separately and have its own requirements documents and its own development life cycle. A reasonable starting point in the development of such a model might be the software development life cycle given within IEC 61508 and shown in Figure 1. This is largely the standard "V-model" life cycle, with which most engineers will be familiar. For those not acquainted with this standard, the acronym E/E/PES stands for electrical/electronic/programmable electronic system. One could argue that a separate life cycle for data is unnecessary since it is already covered by the existing software life cycle. A powerful argument for this point of view would be if it could be shown that data was currently being developed in line with the life cycle of Figure 1. This would suggest that further guidance or regulation was unnecessary. However, if it could be seen that data was currently being ignored, it would seem to strengthen the authors' claim that a separate life cycle model would have benefits.

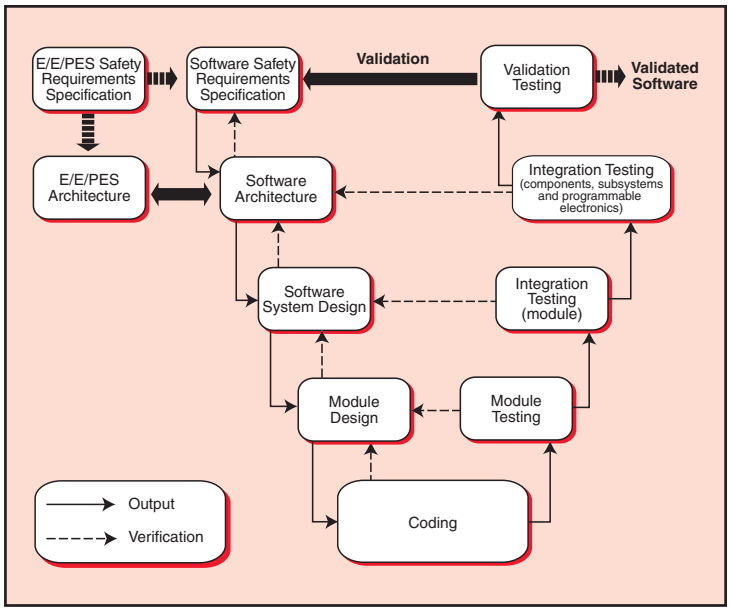

Figure 1 — Software Safety Integrity and the Development Life Cycle, from IEC 61508.

A Survey of Data Development Methods

In order to investigate current development methods for data, a series of structured interviews was carried out, with representatives from a range of industries. The interviews were confidential, to allow for frank descriptions of the company's operation. The industries/sectors involved were:

- Railway command and control systems
- High-integrity railway interlocking
- Underground railway systems
- Process control systems
- Air traffic control systems
- Urban road traffic signalling systems
- Electrical engineering systems
- Safety regulator systems

In all cases, the people questioned were senior engineers with many years of experience within their industry. They were therefore able to give an authoritative view on the development methods being used within their organizations.

Results from the Interviews

The survey produced a great deal of information on the development of data-driven systems, and demonstrated, as expected, that these are often developed differently from more conventional safety-related systems. One of the strongest (and perhaps most significant) points raised by the survey is that hazard analysis is often not applied to data in the same way that it is applied to other system elements. This means that the possible failure modes are not identified, and the consequences of such failures are not studied.

Similarly, it is common not to apply integrity requirements to data. This omission masks the need to demonstrate that data has been developed to an appropriate level of quality.

The survey also suggests that the development process changes significantly with time. When a data-driven system is applied for the first

or second time, the developers tend to be involved in this process and to contribute directly to the work involved. The developers are therefore able to give guidance on the implementation methods used, and on the intent behind its construction. In a sense, these early applications form part of the final validation of the system, confirming that it satisfies its requirements in an actual application.

Provided that these early implementations are successful, the developer's involvement in the installation process will normally cease. Later applications will not have the benefit of the input from those who created the system and will need to rely on documentation and an understanding of the developer's intent. As the system is more widely applied, its ability to be tailored to a given situation may result in its being used in circumstances that were not envisaged by the original design team.

It could be argued that each new application of a general-purpose, data-driven system is a unique system, and that each should be independently verified and validated in full to ensure that it is safe and that it satisfies its requirements. However, in practice this is not done. Justification of the system is normally based on the assumption that the configuration data represents an essentially independent module within the system. Since the remainder of the system has been validated in another situation, it is assumed that changing the data only requires that the data be separately validated.

Unfortunately, while it would be possible to design a system to allow the data to be seen as a separate module that could be validated independently, the survey shows that this is often not the case. Many applications rely on data that appears to have no modular structure and that is used in a very poorly defined manner. Under these circumstances, small changes to the data can have significant and unpredictable effects on the system. In such cases, even minor changes to the data would seem to require that the entire system be retested and validated — not just the modified data.

"Perhaps the most worrying finding is that hazard analysis is often not applied to configuration data in the same way that it is applied to other system elements."

Another problem is that the data associated with many systems is not in a form that allows it to be validated separately from the complete system. The survey shows that data often does not have defined requirements, structure or function that would allow it to be validated as a separate entity. In such situations, it can only be investigated as part of the complete system. In these circumstances, one can only determine the safety of a unique set of data by investigating (validating) the complete system.

An interesting finding of the survey is that data-driven systems would seem to be more likely to be used in situations where they interact with other data systems. They therefore tend to contain data interfaces to other systems within an organization. Data passing through these interfaces poses its own unique problems for system integrity and safety. One only has to think of examples such as railway signalling or air traffic control to see how safety is reliant on the quality and timeliness of such data.

A final observation is that data-driven systems tend to be larger in scale than other systems, increasing the need for effective configuration management.

Conclusions from the Survey

The findings of the survey suggest that data within data-driven systems is often *not* being developed in the same way as application software. It also suggests that in many cases the data is not being developed and managed in a way that would satisfy the requirements outlined in IEC 61508, or other standards, for the development of software.

Perhaps the most worrying finding is that hazard analysis is often not applied to configuration data in the same way that it is applied to other system elements. This inevitably leads to a situation where data faults are not identified as significant system hazards.

A failure to identify data-related hazards means that these are not covered by the safety requirements of the system. This, in turn, means that the system architecture, and system design, will not attempt to deal with these hazards. If one does not identify data faults as a significant hazard, then no effort will be put into avoiding, removing, detecting or tolerating such faults.

Also of concern is the fact that, in many cases, no integrity requirements are being applied to data. This seems to imply that data faults are seen as unimportant. When an integrity classification is applied to a system element (such as hardware or software), this brings with it an expectation that faults within those elements will be dealt with in a manner appropriate to that integrity level. For example, IEC 61508 has target failure rates for each of the safety integrity levels. A failure to assign integrity requirements to data ignores the obvious importance of this system element.

Another major finding of the survey relates to the verification and validation of systems that have been configured for a particular situation through the use of data. In such situations, it is not normal to fully validate the configured system, but to rely heavily on confidence gained by validating the system without the data, or with a different data set. This approach would seem to assume that either the data is a completely separate module that can be investigated separately, or that the safety of the system is not affected by the data. Both of these assumptions would seem to be invalid.

In many cases, companies take great care in the production of configuration data, but the techniques used tend to be selected in an unsystematic manner. This may be because little guidance is available within the literature to aid this choice.

Tackling the Problems of Data

It is clear that the management of data in data-driven, safety-related systems is not always receiving the attention that it should. For this reason, the authors suggest that more specific guidance is required for this system element. We propose that data should be specifically identified as a system element within standards such as IEC 61508, and that explicit and unambiguous guidance should be given on appropriate methods for its specification, design, implementation, verification and validation.

One way of encouraging engineers to look specifically

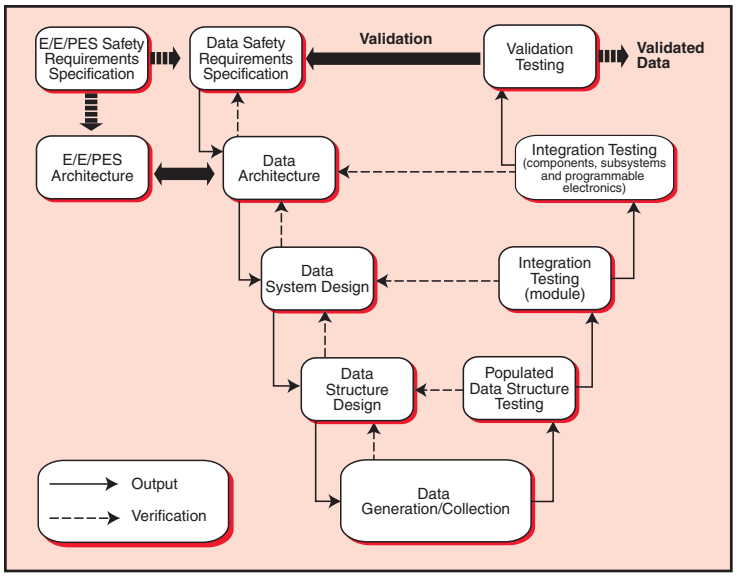

Figure 2 — A Possible Development Life Cycle for a Generic Application of a Data-Driven System.

at the management of data is to assign to it a dedicated development life cycle model. Figure 2 shows a possible life cycle, based on the software development life cycle of IEC 61508.

The life cycle of Figure 2 does not show hazard and risk analyses as a separate phase, since these tasks are carried out throughout the development process. However, the identification of a "data safety requirements specification" will require that hazard and risk analyses be carried out at an early stage in the development process. The data safety requirements will provide an input into the planning of the overall data architecture and may require such features as data fault tolerance.

A key recommendation is that the integrity requirements of the data should be specified explicitly. This will place a requirement on the developer to demonstrate that the data has been developed in a manner consistent with the specified data integrity level. It will also require that the developer show that data faults have been considered and dealt with appropriately.

More detailed aspects of the design will include consideration of the data structures to be used. Here the form of the life cycle model encourages engineers to consider the need for verification of the populated structures at a later time. Experience shows that many existing systems use poorly structured data that makes verification impossible. Such techniques would not be tolerated in the production of executable software, and should not be acceptable within data management.

The generation or collection of data is clearly an important part of data management (although it is not the only part). Care must be taken to ensure that the methods used are appropriate for the safety integrity level of the overall system. In some applications, data will be generated or computed automatically, while in others it will be produced manually. In either case, thought must be given to the required accuracy of the data and the allowable error rates. It is also vital that the origins of the data are recorded to establish traceability. This traceability will allow error correction at the data source and will also be an important part of any subsequent safety justification.

The need for verification of the data is likely to place considerable constraints on the way that it is produced and stored. If one looks at the corresponding situation in the production of executable software, we know that the use of low-level languages is discouraged, since they produce poorly structured software that is likely to contain errors and which is hard to verify. In the same way, requirements for verification will require that data is produced and structured in a manner that permits verification.

Software verification makes use of a range of dynamic and static test tools, and it is likely that a similar range of tools will be needed for the verification of data. In particular, the production of "static data analysis" tools is seen as being very important. It is likely that such tools will require that data is structured, and perhaps annotated, to allow effective verification.

The production of a *data safety requirements specification* will automatically influence the validation process, since the developers will need to demonstrate that issues contained within that document are addressed within the implementation.

While the use of a dedicated data life cycle may assist in the development of a generic data-driven system, it does not tackle the specific problems associated with the adaptation of that generic system to suit a particular situation. One of the issues raised in the survey is that although appropriate verification and validation methods may be used for the generic case, they are not always applied to each application-specific instance of the system. One way of tackling this problem is to have a development life cycle model for the *application* that is separate from that of the *generic system*. Separating the application from the generic system in this way allows individual guidance or requirements to be applied to the development of these two distinct aspects of the system.

Figure 3 shows a possible life cycle model for an application-specific instance of a data-driven system. This removes those activities related to the development of the generic application and emphasizes those tasks related to ensuring the safety of a particular application.

The left-hand side of the life cycle of Figure 3 clearly

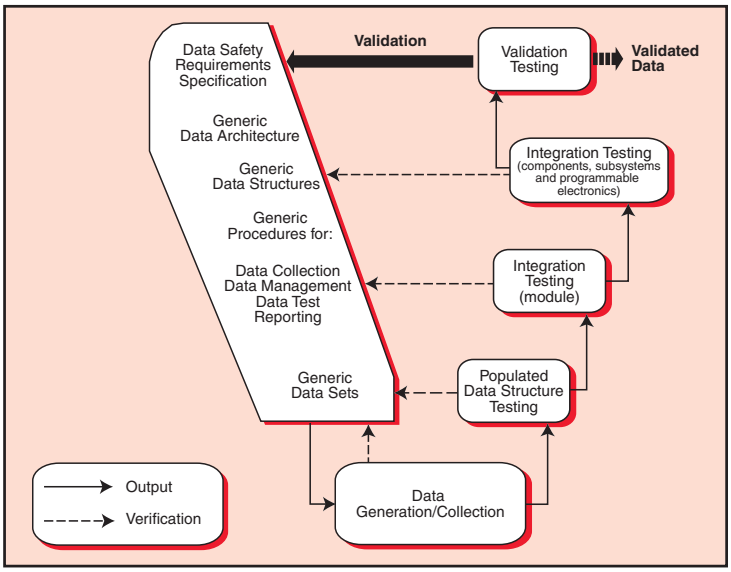

Figure 3 — A Possible Data Development Life Cycle for an Instance of a Data-Driven System.

represents the design elements of the development of the data. In a system formed by configuring a generic application, this work will have been performed at some time in the past. However, it is essential that those responsible for configuring the system have access to the various deliverables from this work. These include the data safety requirements specification, the data architecture and the data structures, but also defined procedures for the collection, management and testing of the data. Other deliverables should include details of an appropriate reporting structure. For example, a data test report should have been created and be awaiting data test results. Some mechanism must also exist to ensure that information gained during the development and use of an individual system is fed back to provide inputs to future development of the generic aspects of the system.

While it would seem clear that these deliverables would be required for the correct configuration of a data-driven system, experience shows that these are not available in many (perhaps most) instances. The use of a well-documented life cycle model of this type might help to alleviate this problem.

The life cycle models described above are based on the generic standard IEC 61508. While this is a widely used standard, it does not meet with universal acceptance. However, the principles outlined above could also be applied to the life cycle models used within other standards to produce equivalent ways of describing the process of data management.

It is inevitable that individual industrial sectors will have different requirements and practices for the use and production of data. Therefore, while generic standards can give general guidance on matters related to data, industry-related standards will inevitably be needed to give more specific information.

Validating Data-Driven Systems

The task of validating a particular instance of a generic system might be simplified by producing a generic safety case that covers the product, a process-based safety case that covers data management (including any proposed regular data updates) and a separate supporting document that relates to a particular application or instance. This supporting document could then be updated to represent the particular details of an individual installation. The generic part of the safety case would need to argue (and demonstrate) that changes to the data would not affect overall system safety. This might require that such changes could be shown to have a limited scope for affecting the operation of the system and that faults within the data component could be adequately detected by testing. It is likely that such an argument would require that the data was adequately structured and validated to ensure its integrity.

Since data-driven systems are often complex, they may benefit from visualization techniques that offer a high level of abstraction. One approach to this problem uses *patterns* to represent commonly used (and reused) components. This technique has been applied to software architectures and configuration management, where it can help identify bad architectures or practices (which are known as *antipatterns*). Patterns have also been applied to the reuse of common structures within safety case arguments [Ref. 7]. Such reuse would seem to be of considerable benefit in applications where a generic system is applied in a range of situations. It is also possible that patterns may have relevance in the development of data architectures and data structures.

Conclusion

The widespread use of COTS is leading to an increasing number of systems that make use of large amounts of data. A survey covering a range of industries suggests that this data component is not always being developed in a manner that is consistent with the integrity requirements of the system in question. One reason for this could be that data is largely ignored within the various generic and industry-specific standards.

Within data-driven systems, data should be considered as a distinct system element with its own requirements documents and life cycle. Generic standards such as IEC 61508 should also give specific guidance on the design, production and verification of data. This, it is hoped, will encourage engineers to give the production and management of data the attention it deserves.

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Neil Storey is a Director within the School of Engineering of the University of Warwick in the U.K., and is also a Fellow of the British Computer Society (BCS) and a Chartered Engineer. His primary research interests are in the area of safety-critical computer systems. A member of the BCS Expert Panel on Safety-Critical Systems, he has a large number of publications in the safety area. Neil is also the author of several textbooks on electronics and safety, including *Safety Critical Computer Systems* published by Addison-Wesley.

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The authors received a Best Paper award at the 20th International System Safety Conference in Denver in 2002.

WORD JUMBLE

by Tom Muro

G I T M A R L O H

N I T O A C M O B I N

I A S T L F I T A C

M R P C E F O N A R E

T E N S M E E L

What the bridegroom/project planning engineer needed to meet on the big day...

His _____ _____

Answer on page 36

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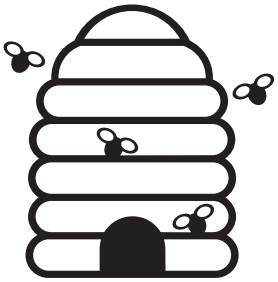

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Solution from page 14.

ALGORITHM

COMBINATION

FATALISTIC

PERFORMANCE

ELEMENTS

What the bridegroom/project planning engineer needed to meet on the big day...

His FORMAL SPECIFICATIONS