INTRODUCTION

As a general rule, all engineering applications use mathematics or mathematical tools as a basis for their development. However, software engineering is an exception to this rule.

Formal methods (FM) are a collection of methodologies and related tools, geared to the production of software employing a mathematical basis. There are a number of different formal methods each having its own methodology and tools, especially a specification language.

We can say that FM are “mathematically based techniques for the specification, development and verification of software and hardware systems” (retrieved on October 15, 2003, http://foldoc.doc.ic.ac.uk/foldoc).

Most FM are based mainly on specifications – for which they normally have a language to express it. Sometimes, there is also a method to use the language in the software development process.

The aims of FM can vary according to the different methodologies, but they all shared a common goal: the production of software with the utmost quality mainly based on the production of software that is error free. To achieve this, the different FM have developed not only a theory but also different tools to support the formal process.

FM can cover all of the steps of the life cycle of a software system development from requirement specification to deployment and maintenance. However, not all FM have that capacity.

Table 1. Summary of specification language characteristics

<table>
<thead>
<tr>
<th>Model-oriented</th>
<th>Property-oriented</th>
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<tr>
<td>Based on mathematical domains. For example, numbers, functions, sets, etc. Concrete.</td>
<td>Based on axiomatic definitions. Abstract.</td>
</tr>
<tr>
<td>Imperative or State-oriented. Allows the use of variables.</td>
<td>Action. Time can be considered in the specification. There are several ways of doing this: considering time as linear or branching, synchronous, asynchronous, etc.</td>
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<tr>
<td>Applicative. Does not allow the use of variables.</td>
<td></td>
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<tr>
<td>Static. Do not include provisions for handling time.</td>
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Formal Methods in Software Engineering

Table 2. Summary of semantic definitions styles of specification languages

<table>
<thead>
<tr>
<th>Style</th>
<th>Description</th>
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<tr>
<td>Operational</td>
<td>Concrete, not well suited for proofs.</td>
</tr>
<tr>
<td>Denotational</td>
<td>Abstract, well suited for proofs.</td>
</tr>
<tr>
<td>Axiomatic</td>
<td>Very abstract, normally only limited to conditional equations.</td>
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about designs. For example, aeronautical engineers make extensive use of computational fluid dynamics (CFD) to calculate and predict how particular airframe designs will behave in flight. We use the term ‘formal methods’ to refer to the variety of mathematical modelling techniques that are applicable to computer system (software and hardware) design. That is, formal methods is the applied mathematics of computer system engineering, and, when properly applied, can serve a role in computer system design analogous to the role CFD serves in aeronautical design.

Formal methods may be used to specify and model the behavior of a system and to mathematically verify that the system design and implementation satisfy system functional and safety properties. These specifications, models, and verifications may be done using a variety of techniques and with various degrees of rigour. The following is an imperfect, but useful, taxonomy of the degrees of rigour in formal methods:

- **Level-1:** Formal specification of all or part of the system.
- **Level-2:** Formal specification at two or more levels of abstraction and paper and pencil proofs that the detailed specification implies the more abstract specification.
- **Level-3:** Formal proofs checked by a mechanical theorem prover.

Formal proofs, checked by a mechanical theorem prover, represent the use of mathematical logic or a specification language that has a formal semantics to specify the system. This can be done at several levels of abstraction. For example, one level might enumerate the required abstract properties of the system, while another level describes an implementation that is algorithmic in style.

Level 2 formal methods goes beyond Level 1 by developing pencil-and-paper proofs that the more concrete levels logically imply the more abstract–property oriented levels. This is usually done in the manner illustrated below.

Level 3 is the most rigorous application of formal methods. Here one uses a semi-automatic theorem prover to make sure that all of the proofs are valid. The Level 3 process of convincing a mechanical prover is really a process of developing an argument for an ultimate skeptic who must be shown every detail.

Formal methods is not an all-or-nothing approach. The application of formal methods to only the most critical portions of a system is a pragmatic and useful strategy. Although a complete formal verification of a large complex system is impractical at this time, a great increase in confidence in the system can be obtained by the use of formal methods at key locations in the system. (Retrieved October 31, 2003, http://shemesh.larc.nasa.gov/fm/fm-what.html)

NASA as well as other government bodies in the USA, Europe and elsewhere are using FM especially in avionics and systems where the utmost reliability is needed. Some examples from NASA are: Small Aircraft Transportation System (SATS), Formal Analysis of Airborne Information for Lateral Spacing (AILS), also NASA’s contractors use FM. For more information on this and other projects, see http://shemesh.larc.nasa.gov/fm/.

As it is stated previously in NASA’s definition of the levels of degree of rigour, they are imperfect. Others exist. Most of the FM included in the following text have as an integral part not only a language but also a methodology included, and most of the time this methodology implies different levels of rigour in its use. For example, RAISE – that have its own method – presents three degrees of formality (The RAISE Method Group, 1995):

- **formal specification only**, where formality is only applied to the specification procedure.
- **formal specification and rigorous development**, where formality is applied to the specification procedure as above, and rigour to the development process. This means that the developer starts writing abstract specifications, goes on developing more concrete ones and recording the development relations between them. These relations are then examined, however they are not justified.
- **formal specification and formal development**, it is the extension of the previous degree to do the justification as well.

Here is a not all-inclusive list of FM:

- **B–Method** “B is a formal method for the development of program code from a specification in the Abstract Machine Notation” (Retrieved October 23, 2003, from http://www.afm.lsbu.ac.uk/b/).
- **CSP** (Communicating Sequential Processes) “process algebra originated by C. A. R. Hoare (http://www.afm.lsbu.ac.uk/csp/).
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