Verified Software for Ubiquitous Computing[1]
— a Proposed *VSTTE/Ubiquitous Computing* Foothill Project —

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Abstract

We sketch a project that is to be pursued over the next 15 years and, hopefully, by partners on five continents: (i) the Pacific: Australia, New Zealand; (ii) Asia: China, India, Japan, Korea, Macau, Singapore; (iii) Europe (Austria, Denmark, England, France, Germany, Ireland, Italy, Portugal, Sweden, Switzerland) and (iv-v) North and South America (Argentina, Brasil, Canada, USA).

Sets of commensurate descriptions of transportation domains shall be developed and analysed. A domain theory of, it is proposed, transportation shall thus emerge. Based on these descriptions (formalised using a set of integrated formal notations) a set of commensurate prescriptions of requirements for a ubiquitous computing system for automated highways shall be developed. The "commensurateness" of the different requirements prescriptions and their relations to the commensurate domain descriptions shall likewise be proved. Eventually these requirements shall be programmed with program annotations relating program statements to respective requirements and domain models.

In this paper we outline and discuss implications of the above.

There are two versions of this document.

A short version is the draft of an invited paper for the First Asian Working Conference on Verified Software, UNU-IIST, Macau, 29–31 October, 2006[2].

A long version aims at informing potential project partners in, we hope, sufficient detail so as to help them decide to join the project.

This is the short version.

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[1] Invited talk for the First Asian Working Conference on Verified Software, UNU-IIST, Macau, 29–31 October, 2006.

[2] http://www.iist.unu.edu/www/workshop/AWCVS2006/

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1 The Backgrounds

1.1 "A Gleam in the Eye"

Three strands appear to come together in this project proposal.

One initiation point for this research and advanced development proposal is the author's fascination with domain engineering as applied to transportation. Initially to the railway sub-domain. More generally, and later, with the transportation domain. And, in this proposal, the instantiation of this transportation domain to the concept of "the automated highway".

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Two other initiation points were Tony Hoare's similar obsession with VSTTE, "a million lines of verified code", and Robin Milner's "lifting" of the concerns of ubiquitous computing to elegant heights.

More than 30 years of quest for provably correct software, since the days of the birth of VDM at the IBM Laboratory, Vienna, Austria, is embodied in the project.

1.2 VSTTE: Verified Software: Theories, Tools and Experiments

The idea at the root of the VSTTE grand challenge is that of a verifying compiler. That compiler accepts annotated code. The annotations are, for example, like pre- and post-conditions (say in a Hoare-style logic). The annotations are meant to express requirements and assumptions about the machine and the environment of the machine on which the code is executed. The verifying compiler is then expected to prove, that is, to verify, that the annotated code indeed satisfies the annotations. We refer to [1, 2]

1.3 Ubiquitous Computing: The Automated Highway

By 'ubiquitous computing' we shall here understand the presence of computation (and communication) "everywhere". And by 'the automated highway' we shall specifically understand the use of computation and communication in every possible aspect of automating the orderly (safe and efficient) movement of cars along a net of highways. This latter implies the availability of sensors and actuators along and possibly above and/or "outside" the highway net and in all vehicles moving along this net of highways.

Ubiquitous computing (ubicomp, or sometimes ubiqcomp) integrates computation into the environment, rather than having computers which are distinct objects. Other terms for ubiquitous computing include pervasive computing, calm technology, and things that think. Promoters of this idea hope that embedding computation into the environment and everyday objects would enable people to move around and interact with information and computing more naturally and casually than they currently do. One of the goals of ubiquitous computing is to enable devices to sense changes in their environment and to automatically adapt and act based on these changes based on user needs and preferences. We refer to [3]

1.3.1 The Automated Highway

Just very briefly: an automated highway system or Smart Road, is an advanced intelligent transportation system technology designed to provide for driverless cars on specific rights-of-way. It is most often touted as a means of traffic congestion relief, since it drastically reduces following distances and thus allow more cars to occupy a given stretch of road. We refer to [4]

1.4 Domain Engineering

Section 3.2.1 should probably be read first. By a domain model we understand an abstraction of some reality, something which exists, and as it is conceived to be. A domain model is typically expressed by both a precise, and as here English narrative and a formalisation. If the formalisation is in logic then one of the set of models which satisfy the logic is what we mean by "the domain model". If the formalisation is in some model-oriented specification language, such as B [5], VDM-SL [6, 7, 8] or Z, then the semantics of these languages explicitly

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designates the model(s). To create such a model, or, typically, set of models, one needs to acquire domain knowledge, analyse it, and then bring the acquisition and the analysis together in a description such as for example given in Sect. 3.2.1 and according, for example, to the principles, techniques and tools as outlined to some depth in Chap. 11 of [9].

2 The Triptych Dogma

2.1 The Dogma

Before software can be designed its requirements must be understood. Before requirements can be prescribed the application domain must be understood.

Hence the "idealistic" triptych dogma:

- $\mathcal{D}$**:** First one must establish a proper, comprehensive domain theory for the application area — here transportation in general.
- $\mathcal{R}$**:** From such a domain theory one can, as we show in Chaps. 18–25 of Vol 3 of [10, 11, 9], i.e., [9], "derive" domain (i.e, functional) requirements.
- $\mathcal{S}$**:** From these again, as we show in Chaps. 26–29 [9], we can decide major structures of the desired software.

2.2 Verification

In proving software, i.e., program code, $\mathcal{S}$, correct with respect to requirements, $\mathcal{R}$, such a proof is always relative to assumptions about the domain, $\mathcal{D}$:

$$\mathcal{D}, \mathcal{S} \models \mathcal{R}$$

To do proper proofs we postulate that proper theories need first be established of the domain and of the requirements.

2.3 Decomposition of Project Effort

The present proposal hinges to some extent on the triptych dogma. But the proposal allows for research groups to focus their contributions "down stream" from domain descriptions and requirements prescriptions, or only on one of these.

Some "Verified Software for Ubiquitous Computing" project groups will wish to focus on one or more of:

- Domain Theories (descriptions and analysis) using one or another approach, including combinations of approaches, other groups on
- Requirements Prescription development from Domain Descriptions and proofs of development "transformations", other groups on
- Requirements Theories (descriptions and analysis), or on
- Software Design development from Requirements Prescriptions and proofs of development "transformations", or on

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- Program Code Annotation and Verification — from Domain Descriptions and Requirements Prescriptions

Project management is then needed to secure that it all "hangs together", forms a whole.

3 The Project Proposal

3.1 Summary

Section 2.3 suggests a number of project components:

1. Sets of commensurate correlated informal and formal descriptions of transportation domains shall be developed and analysed. We refer to Sect. 3.2.
2. A theory of transportation shall thus emerge. That theory shall explain and prove what precisely is meant by commensurateness.
3. Based on these descriptions (formalised using a set of integrated formal notations) a set of commensurate prescriptions of requirements for a ubiquitous computing system for automated highways shall be developed.
4. The "commensurateness" of the different requirements prescriptions and their relations to the commensurate domain descriptions shall likewise be proved.
5. Eventually these requirements shall be programmed with program annotations relating program statements to respective requirements and domain models.
6. The programs with annotations shall be processed by a verifying compiler and the program code shall be automatically proved correct wrt. the program annotations.

3.2 Domain Theories

To get a grasp on what a domain description might entail we give in Sect. 3.2.1 an example domain description. We refer to Item 1 Sect. 3.1.

3.2.1 A Domain Model

Let us take a reasonably comprehensive look at an albeit simple domain description, namely that of a simple transportation net and its traffic. We refer to

- The BCS FACS Journal, December 1005
  http://www.bcs-facs.org/newsletter/facts200512.pdf

for a more detailed exposition of the below description.

(1.) A transportation net (N) consists of segments (S) and junctions (J). (2., 3.) That is, from a net one can observe the set of all segments and the set of all junctions. (4.) There is at least one segment and two (distinct) junctions in any net. (5.) Segments and junctions have unique identifications (Si, Ji)[3]. (6.,7.) One can observe segment and junction identifiers from

[3]Segment and junction identifiers can be thought of as summarising the distinct spatial location of that which they identify.

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segments, respectively junctions. (8., 9.) To avoid "junk" being models of our specification we must insist that the number of segments [junctions] of a net equals the number of segment [junction] identifiers of that net. (10., 11.) Segments are delimited by a pair of junctions, and from a segment one can (thus) observe the pair of junction identifiers of the delimiting junctions. (12., 13.) Junctions connect to one or more distinct segments, and from a junction one can (thus) observe the set of one or more respective segment identifiers.

type
1. N, S, J
value
2. obs_Ss: N → S-**set**
3. obs_Js: N → J-**set**
axiom
4. ∀ n:N • **card** obs_Ss(n) ≥ 1 ∧ **card** obs_Js(n) ≥ 2
type
5. Si, Ji
value
6. obs_Si: S → Si
7. obs_Ji: J → Ji
axiom
8. ∀ n:N • **card** obs_Ss(n) ≡ **card** {obs_Si(s)|s:S • s ∈ obs_Ss(n)}
9. ∀ n:N • **card** obs_Js(n) ≡ **card** {obs_Ji(c)|j:J • j ∈ obs_Js(n)}
type
10. Jip = {|{ji,ji′}:Ji-**set** • ji≠ji′|}
value
11. obs_Jip: S → Jip
type
12. Si1 = {|sis:Si-**set•card** sis ≥1|}
value
13. obs_Sis: J → Si1
axiom
14. ∀ n:N, s:S • s ∈ obs_Ss(n) ⇒
15. **let** {ji,ji′} = obs_Jis(s) **in**
16. ∃! j,j′:J • {j,j′}⊆obs_Js(n) ∧ j≠j′ ∧
17. obs_Si(s) ∈ obs_Sis(c) ∩ obs_Sis(c′) **end**
18. ∀ n:N, j:J • j ∈ obs_Js(n) ⇒
19. **let** sis = obs_Sis(c), ji = obs_Ji(j) **in**
20. ∃! ss:S-**set** • ss⊆obs_Ss(n) ∧ **card** ss=**card** sis ∧
21. sis = {|obs_Si(s)|s:S•s ∈ ss|} **end**

(14.–17.) For every segment of a net there exists exactly a set of distinct junctions of that net whose identifiers are those observable from that segment, and (18.–21.) – vice versa – for every junction of a net there exists exactly a set of distinct segments of that net whose identifiers are those observable from that junction.

The above description covers just the net of its junction-connected segments.

(22.) Paths are triples of (junction,segment,junction) identifiers, and routes are sequences of paths. (23.–25.) 'paths(n)' expresses all paths of a net. (27.–30.) A route is is a finite

sequence of paths such that adjacent sequence triples designate adjacent paths, that is, paths sharing a junction identifier (well-formedness). (32.–35.) 'routes(n)' expresses all routes of a net, that is, a possibly infinite set since routes my be cyclic. Any path is a route. If r and r' are routes such that the last path of r shares last junction identifier with the first junction identifier of the first path of r', then their concatenation is a route.

```
type
22. P = Ji × Si × Ji
value
23. paths: N → P-set
24. paths(n) ≡
25.   {(ji,si,ji′)|s:S,ji,ji′:Ji,si:Si• s ∈ obs_Ss(n)∧{ji,ji′} ∈ obs_Jis(s)∧si=obs_Si(s)}
type
26. R = {|r:P*•wf_R(r)|}
value
27. wf_R: P* → Bool
28. wf_R(r) ≡
29.   ∀ i:Nat • {i,i+1}⊆inds(r) ⇒
30.     let (_,_,ji)=r(i), (ji′,_,_)=r(i+1) in ji = ji′ end
31. routes: N → R-infset
32. routes(n) ≡
33.   let rs = {⟨p⟩|p:P•p ∈ paths(n)}
34.       ∪ {r^r′|r,r′:R•{r,r′}⊆rs∧wf_R(r^r′)} in
35.   rs end
```

(36.) The state of a segment is a either an empty set, or a singleton set, or a set of two "reversed" pairs of the identifiers of the two junctions to which the segment is connected. An empty set designates that the segment is closed for traffic. A single pair $(j_i, j_{i'})$ designates that the segment is open for traffic from the junction identified by j_i to junction identified by $j_{i'}$. A double pair designates that the segment is open for traffic in both directions. (37.) The state of a junction is a set of pairs of identifiers of the segments that are connected to that junction. If (s_{i_j}, s_{i_k}) are in the state then it means that traffic can traverse the junction from the segment identified by s_{i_j} to the segment identified by s_{i_k}. (38.–39.) From a segment [junction] one can observe the state of the segment [junction]. (40.–43.) One can speak of and observe the state space of a segment [junction]. (44.–45.) The current state of a segment [junction] lies in the state space of that segment [junction].

```
type
36. SΣ = {|jip:(Ji×Ji)-set•card jip≤2∧card jip=2⇒(ji,ji′)∈ jip⇒(ji′,jip)∈ jip∧ji≠ji′|}
37. JΣ = (Si×Si)-set
value
38. obs_SΣ: S → SΣ
39. obs_JΣ: J → JΣ
type
40. SΩ = SΣ-set
41. JΩ = JΣ-set
value
42. obs_SΩ: S → SΩ
```


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43. obs_JΩ: J → JΩ

axiom

44. ∀ s:S • obs_SΣ(s) ⊆ obs_SΩ(s),
45. ∀ j:J • obs_JΣ(j) ⊆ obs_JΩ(j)

(46.) Time, vehicles and lengths are introduced. Time is considered a dense, ordered set. (47.) Fractions are reals in the inclusive range 0 to 1. (48.) A (vehicle) position is either at a junction or some fraction a segment (down, from fj_i to tj_i, implicitly) identified by this pair of identifiers of the junctions to which the segment is connected. (49.) Real [observed] traffic is a continuous function [discrete map] from time to pairs of nets and positions of vehicles. (50.) Segments have lengths. (51.–58.) The lengthy axiom expresses one aspect of traffic: that positions are indeed positions of the net.

type

46. T, V, L
47. F = {|f:**Real**•0≤f≤1|}
48. P == mkP_at_J(ji:Ji) | mkP_along_S(fji:Ji,f:F,tji:Ji)
49. rTF = T → (N × (V $\overrightarrow{m}$ P))
50. oTF = T $\overrightarrow{m}$ (N × (V $\overrightarrow{m}$ P))

value

51. obs_L: S → L

axiom

52. ∀ tf:(rTF|oTF) •
53. ∀ t ∈ **dom** tf •
54. **let** (n,vps) = tf(t) **in**
55. ∀ p:P • p ∈ **rng** vps ⇒
56. **case** p **of**
57. mkP_at_J(ji) → ji ∈ obs_Jis(n),
58. mkP_along_S(jf,_,jt) → {jf,jt}⊆obs_Jis(n)
    end end

The formalisation of other aspects of traffic are left as an exercise: (i) that real [observed] traffic is truly continuous [monotonic] (including: moving from open segments through "open" junctions onto open segments and: vehicles do not "jump around"), (ii) that there are no "ghost" vehicles (that is, that a vehicle which is in the traffic at two distinct times are in the traffic at all times in between these, etcetera.

3.2.2 Real Highway Transportation Nets

The model above has been simplified to fit this paper. A more realistic model, one that can serve as a domain model for the requirements of an automated highway, would model (i) multi-lane highway segments and junctions, (ii) vehicle lane positions, (iii) vehicles changing lanes, etc.

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3.3 Requirements

3.3.1 General: Co-ordination and Function Requirements

Now, depending on requirements for ubiquitous automated highway computing, a number of co-ordinated requirements prescriptions need be studied, developed, the resulting formal prescriptions analysed — including establishing a theory of the requirements. By "co-ordinated requirements prescriptions" we mean a "set and a co-ordination" which, as a whole, prescribe requirements to an automated highway computing system, but such that individual members of the set ("function requirements") each solve a well-prescribed problem in the context of the co-ordination software (prescribed by the "co-ordination").

We think of the co-ordination requirements and the corresponding software to represent the essence of ubiquity.

3.3.2 Ubiquitous Requirements: Some Speculations

In this section we shall sketch some rather preliminary ideas on some aspects of requirements to automated highways — such aspects, it seem, which may cast light on what we may be an issue of, an "ingredient" in requirements to ubiquitous computing systems.

Let us perform an experiment. Assume traffic "rolling" down a highway. Traffic consists of a number of vehicles passing down a number of opposite lanes, possibly at different velocities, possibly changing lane, overtaking, possibly slowing or speeding up.

Now what might "automation" mean in this case? Well it could mean either of many different things. All vehicles could be coerced into travelling at "same" velocity, or "as much as possible" close to (from below) a desired mean velocity, or be "free to change velocity", and/or be constrained to "near same" (mean) acceleration and deceleration. Etcetera.

Whichever of these are chosen, it seems that each vehicle is expected to register, as is expected done by their drivers today, some composite "picture", a "local state", of the traffic "around" that vehicle, to "some depth", that is, to some distance from that vehicle. Based on such a local state the driver today makes driving (steering, acceleration, deceleration, etc.) decisions. Today drovers do that — thus basically without consulting other drovers' plans (including their local states). In an automated highway computing system one might expect individual as well as communal driving decisions and hence actions to be based on summaries of local states "around" each vehicle, or even global such summaries. Classically one might be able to express such decision outcomes as the result of solving a large number of for example differential equations, or, alternatively, some similar sets of fuzzy control expressions.

One is reminded here of:

- Victor I. Varshavski and Dmitrii Aleksandrovich Pospelov: *Puppets without strings: Reflections on the evolution and control of some man-made systems*, Mir Publishers, Moscow, 1984 (English edition: Mir Publishers, 1988, 294 pages).

An analysis of what is thought to be needed to express (i.e., to monitor and, later, control) local (and "less local") states in domain descriptions and, subsequently in requirements prescriptions should give a rather precise idea about the need for computing system sensors and actuators.

Everyone can speculate: mention this and that kind of sensors and actuators, but only a thorough domain analysis and a "therefrom derived" requirements analysis can tell us exactly the properties we need of those sensors and actuators.

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3.3.3 Further on Requirements

In this paper we shall not further attempt to formulate further requirements. To do this properly requires, in our mind, very close collaboration with the Cambridge University group of Prof. Jon Crowcroft. We refer to:

- http://www-dse.doc.ic.ac.uk/Projects/UbiNet/GC/Manifesto/fp-automatinghighway.html
- http://www-dse.doc.ic.ac.uk/Projects/UbiNet/GC/Manifesto/road.pdf

It is hoped that some of the groups involved in Domain Theories will also want to become involved in th Requirements-related projects.

And it is expected that this, the Requirements effort, will be closely collaborating with the Ubiquitous Computing Automated Highway project as referred to above.

3.4 Software

We postulate, as we did in Sect. 3.3, that the resulting computing system software consists of the co-ordination (the ubiquitous) software and its many "isolated" packages. We speculate that these "isolated" software packages can each be developed in isolation — provided that a stable interface to the co-ordination software can be established — and that they can each be verified in, i.e., assuming this context.

We shall not speculate further on the software possibly emanating from this proposed project other than the above single paragraph.

3.5 Overview of Project Components

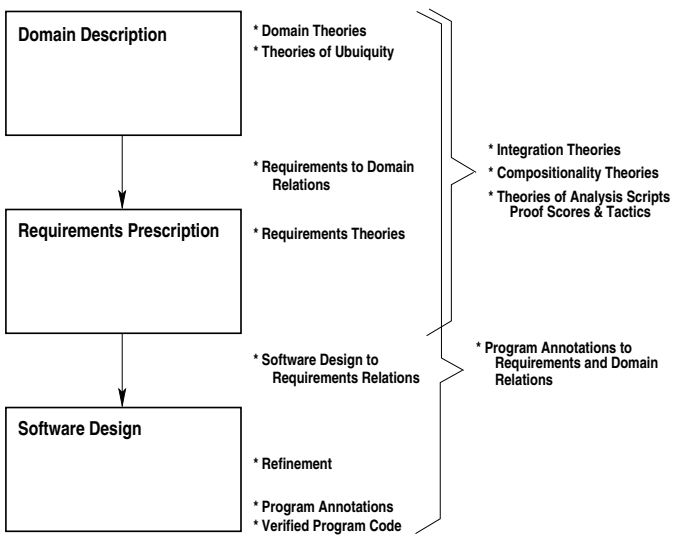

Figure 1: Project Components

4 Challenges

There is an overall challenge:

> **Challenge # 0. Verified Software for Ubiquitous Computing:** The overall challenge is to both understand the concept of ubiquitous computing and contribute to the verified software concept.

And there are a number of constituent challenges. The latter contribute to the former. We formulate some of the latter as we expect different research groups around the world to more readily "catch on" to the latter challenges than to the former.

4.1 Commensurate Specifications

The example given in Sect. 3.2.1 was expressed in the RSL formal specification language [12, 13, 10, 11, 9]. There are other formal specification languages. To wit: Alloy [14], B [5], CafeOBJ [15, 16, 17], Casl [18, 19, 20], CSP [21, 22, 23, 24], VDM-SL [6, 7, 8], RSL [12, 13, 10, 11, 9], or Z [25, 26, 27, 28] are some of the better known.

Some (verified software for ubiquitous computing project groups) will specify their domains or requirements in one of these languages. Others in another of these languages.

> **Challenge # 1. Commensurate Specifications:** It is therefore a challenge to show relations between some pairs of specifications purporting to describe "the same thing", that is, to embody the comparable theories. How exactly such coexisting different notation formal descriptions can be so compared is an open question.

4.2 Integrated Specifications

The example given in Sect. 3.2.1 captures only some basic entities of transportation nets and some basic characteristics of traffic (a behaviour).

To capture such phenomena as the individual behaviour of a vehicle, the monitoring and control of traffic and of traffic signals (i.e., the changing of segment and, in particular junction states, would probably be a mistake. More suitable formal notations should be used. They should then be used in conjunction with some formal textual notation, such as those mentioned in Sect. 4.1.

Which other such possible, "more suitable" notations exists, today, Summer 2006? We suggest that perhaps either one or more of the following may be used: DC (for duration calculus, a temporal logic specification language) [29, 30], message or live sequence charts (MSCs, [31, 32, 33], or LSCs, [34, 35, 36]), Petri nets [37, 38, 39, 40, 41], statecharts [42, 43, 44, 45, 46], TLA+ [47, 48, 49], or other. Some of these other may "be in the works" as of now: being researched and put forward as means for modelling, say, statistical, continuous, chaotic or other phenomena.

Whenever the textual notations of Alloy [14], B [5], CafeOBJ [15, 16, 17], Casl [18, 19, 20], VDM-SL [6, 7, 8], RSL [12, 13, 10, 11, 9], Z [25, 26, 27, 28], or other, are combined with those of, for example, DC [29, 30], MSC [31, 32, 33], LSC [34, 35, 36], Statecharts [42, 43, 44, 45, 46], TLA+ [47, 48, 49], or other, we say that the result is a set of two or more interfacing specifications. The interface may be manifest in for example the following way: In

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specification $S_A^{L_i}$ some identifiers $id_1, id_2, \ldots, id_n$ are claimed to somehow "equivalize" with identical identifiers in specification $S_B^{L_j}$. When this is the case, an obligation arises, namely to show that a suitable equivalence (or satisfaction) relation can be established. Reasoning in one notation "must carry over" into "interfacing" parts expressed in another specification.

Substantial research is done in this are as witnessed by, for example, [50, 51, 52, 53, 54].

A real core issue for this project to study is the relationship between the kind of textual specification languages extensively listed and referenced above and the calculus of classical mathematics — as for example used in automotive engineering: differential equations and the like. It is a challenge to provide as seamless transition from specification in the form of classical applied mathematics, including operations research, and the newer formal specification languages.

> **Challenge # 2. Integrated Specifications:** For specific such interfacing (and thus commensurate) specifications or for general uses of their specification languages, suitable equivalence (or satisfaction) relations must be established (formulated and formally proven).

4.3 Domain Theories

By a domain theory we understand a domain description and a number of theorems that can be proved to hold of what the description models. These theorems are (obviously) proved in the proof system of the notations in which the domain description is expressed.

What could such "interesting" theorems be about? Well, let's try some possible, or potential examples:

- *Kirchoff's Law for Railways:* Assuming that train timetables are modulo 24 hours and that trains run on time, then for any 24 hour contiguous period (i.e., interval) and for every train station it is the case that the number of trains arriving at a station minus the number of trains ending their journey at that station plus the number of trains starting their journey at that station equals the number of trains leaving that station.

- *"No Ghost Trains":* In a domain description of highway traffic along a segment, then for any consecutive times t and t'' and for any vehicle which is in the traffic at those times it is the case that the vehicle is also in the traffic at all times between t and t''.

- *"God does'nt Play Dice":* We assume that the model for traffic is continuous, or at least monotonic over time (either a dense set of points, or, respectively, a discrete set of points with clearly defined "next" time successors. We assume a single lane, one traffic direction segment. If at time t vehicle v_i is "after" vehicle v_j in the traffic along the segment, then at a "next" (i.e., the successor) time t' vehicles v_i and v_j have not reversed their position.

This leads us to formulate:

> **Challenge # 3. Domain Theories:** So, for the domain of transportation (incl. highway transportation) the challenge is to identify and prove "interesting" theorems.

A source of inspiration as to what kinds of theorems to look for in any domain theory seems to be [55]. It is hard for me to think that laws of man-made domains are that fundamentally different from those nature.

4.4 Analysis Scripts: Proof Scores and Tactics

In connection with research around CafeOBJ some insight is gained with respect to "standard" scripts according to which CafeOBJ specifications can, or should be analysed. These are called proof scores. Proof scores are first class CafeOBJ objects. In that sense they are different proof tactics pursued as early as the early days of LCF [56, 57, 58, 59, 60] and is also a core subject of PVS [61, 62] proof work [63].

> **Challenge # 4. Analysis Scripts: Proof Scores and Tactics:** So, for any domain or requirements formalisation the challenge is to find a suitable, reusable set of analysis scripts.

4.5 Ubiquity

"How are the computers in the automated highway system configured and controlled? What tools are needed for design and analysis of constantly adapting and evolving computing system? What theories will help us to understand its behaviour? How do we manage such systems, or even understand them? How do people interact with them and how, in which ways, does this new pervasive technology affect us?"

These are some of the many questions that the Ubiquitous Computing — Science and Design — Grand Challenge initiative is raising.

> **Challenge # 5. Ubiquity:** The proposed Verified Software for Ubiquitous Computing project is expected to contribute to at least the tools are needed for design and analysis of constantly adapting and evolving computing system and to their underlying theory.

4.6 Compositionality

We have made some vague, non-committed references to 'decomposition' of the domain description, the requirements prescription and the software design tasks (the latter in terms of 'isolated' software packages composed with 'co-ordination software'.

> **Challenge # 6. Compositionality:** Does the established computer science work on compositionality, for example as illustrated by [64, 65, 66, 67, 68, 69], apply here? Or must new concepts be developed?

This version of the compositionality concept apply specifically to components and objects.

4.7 Formalisation of Machine Requirements

Machine requirements such as performance, dependability, maintainability, platforms, etc. are not easily formalisable, and, when formalisable (with some difficulty) it is not yet well understood how one "derives" implementations correct wrt. the machine requirements.

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Challenge # 7. Formalisation of Machine Requirements: Ubiquitous computing has very much to do with machine requirements so a special challenge, in the small, and, it appears, as many distinct challenges, is to discover, study and make practically useful principles, techniques and tools of machine requirements and their implementation.

4.8 Requirements to Domain Relations

We claim, and show in Chap. 19 of Vol. 3 [9], that core issues of requirements, what we term the domain requirements and the interface requirements, can be systematically deduced, in interaction between the domain description, the requirements engineers and the client.

Challenge # 8. Requirements to Domain Relations: Although the engineering seems clear it also seems desirable to have a more formal understanding of the relations between requirements prescriptions and domain descriptions, and for a suitable variety of cases — for example such as appears to be offered in the context of software for ubiquitous computing.

4.9 Software Design to Requirements Relations

Many of the relations that are implied here are those that show up, it appears — and to this author certainly — in for example Michael Jackson's seminal work on 'Problem Frames' [70].

Challenge # 9. Software Design to Requirements Relations: So we pose as a challenge to more precisely understand these relations — including formally.

4.10 Program Annotation to Requirements and Domain Relations

A major cornerstone of the VSTTE ideal of program correctness is that of being able to have a machine prove correctness of program code with respect to program code annotations.

We assume (0) that programs are annotated, (1) that the annotations contain elements that clearly relate to $\mathcal{R}$equirements prescriptions, (2) that other (therefrom possibly distinct (?)) annotations that "clearly" relate to $\mathcal{D}$omain descriptions, and (3) that yet other elements (and perhaps the three kinds "overlap") that clearly relate to the programming language. The three, as we postulate, "clearly" identifiable parts appears (and this is yet a postulate) to express properties that then appears to only be provable in relation to respective semantics: ($1'$) The domain theory,($2'$) the requirements theory and ($3'$) the programming language semantics or proof system.

In view of our suggestion:

$$\mathcal{D}, \mathcal{S} \models \mathcal{R}$$

we pose the challenge:

Challenge # 10. Program Annotations: Do the postulates above (1,$1'$–2,$2'$–3,$3'$) hold. How can we express the annotations so as to [most?] clearly designate the three relations? And how is the verifying compiler going to handle all this?

5 Some Observations

Rather unusual for a paper of this kind we bring some extensive comments on an earlier version. Michael Jackson's comments were based in [2].7.

5.1 Michael Jackson's 22 March, 2006 Observations

I would be inclined to go further, in a direction that may offer some insight but would surely be fruitless for influencing the GC. A major difficulty of developing a software-intensive system that interacts with a non-formal physical or human domain is that formalisation is always only approximate. If the system is critical it becomes vital to obtain a very good approximation indeed, and this cannot, in general, be achieved by elaborating the description of domain properties. Instead it becomes necessary to structure a set of domain descriptions, with their attendant requirements and subproblem machines, so that they form an assemblage that in total is a good enough approximation. A simple case is a cascading structure in which the highest element in the cascade describes an idealised domain in which everything works 'as it should' and other elements describe a less idealised domain in which various 'faults' invalidate parts of the assumptions on which the highest element is based.

More generally still, a realistic problem is an assemblage of many subproblems, each addressing a partial requirement on the basis of a partial view of the problem world. The composition of these subproblems raises many concerns such as conflict, interference, incommensurability, and so on, which must be addressed if the subproblems and their solutions are to be combined into the desired system. This complexity of composition inevitably leads to a complexity of software structure. Without addressing this aspect of software structure the developer cannot know whether or not the behaviour of the programmed machine has a good likelihood of ensuring satisfaction of the problem requirements.

One manifestation of this difficulty is that the 'verifying compiler' version of the GC can be seen to depend on the program having an appropriate structure. If the specification is to be embedded in the program the form of pre- and post-conditions and invariants, the program must possess a structure that can accommodate the specification without introducing so many specification variables that the specification itself becomes unintelligible. To take a trivial and grossly simplified example: if a word processor specification includes an invariant on the document that is to be processed, there ought to be a program component corresponding to the whole document. If there are, instead, only components corresponding to operations on the document there will be no place in the program where the document invariant can be written.

5.2 Tony Hoare's July 31, 2006 Observations

The first subsection below is from "random paragraphs" drafted by Tony Hoare, July 2006: Theory for Verified Software, received in an e-mail.

The second subsection below is from an e-mail of It predates "random paragraphs". The bulleted items of the first subsection were part of the June e-mail from which we only bring the advice.

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5.2.1 Random Paragraphs

In any practical software project, theory begins to play a role long before the project starts. Its initial role is to construct a mathematical model of the real world domain in which the projected software will be deployed, without making any commitment to a particular choice of functionality or of implementation technology.

An academic example of a useful domain model is one that describes a range of procedures for the organisation of different kinds of scientific meeting [Fisler]. An industrial example is the domain of scheduling algorithms [Doug Smith]. Domain models (often called ontologies) are of wide application in various e-sciences, to standardise terminology and logical structure of observable data, and to help solve consistency problems between experimental data bases. A domain model may make a contribution towards the analysis of systems composed of other systems (including commercial off-the shelf software). A domain model can provide a framework for classification of a range of software and hardware standards, relating them to each other and to their common purposes. A good example is the ISO Reference Model for Open Distributed Processing. Other serious applications (perhaps too serious for experimentation!) are in the service industries, including retail sales, transport, the health service, and even parts of e-government.

- *A well-structured domain model will describe all aspects of the real world that are relevant for any good software design in the area. It describes possible places to define the system boundary for any particular project.*
- *A domain model makes explicit the preconditions about the real world that have to be made in any embedded software design, especially one that is going to be formally proved.*
- *A domain model describes the whole range of possible designs for the software, and the whole range of technologies available for its realisation. It is a suitable basis for the product line approach to software design and construction.*
- *A domain model provides a logical framework for formalisation and full analysis of a range of possible customer requirements; it reduces the risk of contamination of requirements by the choice of a particular technology of implementation.*
- *A domain model enumerates and analyses the decisions that must be taken earlier or later any design project; it identifies those decisions that are independent and those that conflict, those decisions that must be taken early, and those that can be postponed. Late discovery of feature interactions can be forestalled.*

Research on domain modelling dates back at least as far as the development of VDM, Z, RAISE, and there are now many mathematical formalisms available for describing both the whole and various aspects of a domain model. For example, there are formalisms based on set theory (Z), process calculus (Pi), abstract algebra (ASM), graphical notations (UML), and mixtures of these. Each of these will be suitable for describing different aspects of the domain. It will be a challenge to use them in an appropriate combination, with formal checks of consistency between them. Work on combined use of formalisms may motivate and guide research toward unifying theories of programming.

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An even more important challenge will be to validate a domain model. This may be done by a broad survey of existing implementations, showing that they can all be classified as examples (at least, in approximation) of the model. The model may suggest useful experiments on the real world. The extra effort devoted to the generality of a domain model will be very worth while, because it can be done long in advance of any particular project, and because domain models are much more re-usable than any of their specific implementations.

5.2.2 Comments, I of III

You will find the above issues covered extensively in [9].

5.2.3 Advice

I suggest you give more prominence to these (ed.: the above bulleted) advantages.

A large part of the serious work of domain modelling is a check of the correspondence between the model and the real world. I think your plans should include careful design of the earlier experiments that make this check. This would increase the value of your project far more than actual implementation of any particular one of the possible designs. This particular example project would have to be conducted in close (maybe too close) association with the automobile industry, who are already developing the technology and conducting the experiments – and even delivering the products!

I think your project will have more impact and attract more researchers if you put forward a small range of example projects. They should include a domain taken from the home, one taken from the law (perhaps election law), and perhaps a fragment of an application in (local) government. Different researchers will find different domains more attractive.

The whole point of your example projects is that each of them will deliver results that are much more general than any particular implementation (whether verified or not). Don't spoil this by implementing just one of the possibilities. If you are going to implement anything it should be a program development tool or generator that can be applied to the whole class of implementations, including perhaps an experimental environment for evaluating alternative designs.

Your document contains an example of a fragment of a model written in your favourite language (presumably). Different aspects of the model and design might be well expressed in different conceptual frameworks, for example, process calculus, the pi calculus, algebra, UML, bigraphical systems, etc. Even pictures can be quite helpful. The experienced mathematician is quite skilled in living simultaneously in a variety of modelling presentations. Such diversity should be welcomed, and theorists should be invited to develop techniques and tools that ensure consistency and coherence of the various aspects of the model. Thus domain modelling will provide motivation and source material for another Grand Challenge – Unifying Theories.

In your next step, I would advise you to 'choose your team'. Who are the world-wide leaders in the field whom you would most like to recruit to work on the project? Who are those whose antagonism to the project would be most damaging? The biblical number of apostles is twelve. When you have the leaders helping you, then you can cast your net to the whole community.

5.2.4 Comments, II of III

The current paper has already presupposed this advice.

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5.3 Robin Milner's July 31, 2006 Observations

5.3.1 The E-mail Header

Thank you for putting so much effort into joining two GCs – GC6 and GC2/4 – in the context of automated traffic. I largely agree with what you are saying, and in the note at the end I try to map your way of thinking onto how we have already been thinking in GC2/4. I also comment inconclusively on how we would coordinate this junction; and finally I mention a few things that occurred to me while reading your piece.

I hope we can push this further. I'm puzzled at present as to who on the GC2/4 side will be proactive in the coordination, as opposed to proactive in their own research strand. This whole thing depends on the chance of finding the right individuals!

Here's one thought (but read my remarks below): we could avoid setting up a coordination team at the start, and instead – by luck or judgement – find just ONE (sub)-project that can arise between us because the right individuals need each other. What do you think?

5.3.2 Automated Traffic

You propose a project of 7-10 years on automated traffic. This is a valuable specialisation of the Ubicomp Grand Challenge; the GC must surely involve such special goals. The GC also aims for generic engineering principles and theories that cover a range of specialisations, and this is evident from the general form in which its goals are stated. But I can't see any way to reach these goals other than specialisations like the traffic one.

*The Ubicomp GC proposes that we identify foothill 'topics', or better 'activities', and for each activity there would be many (coordinated we hope, but loosely so) foothill 'projects', each perhaps lasting 3-4 years and tackling a specific aspect of the topic, taking care to involve at least some mix of the three GC themes: Experience, Design and Science. So I see your 'foothill project' more as a 'foothill activity'. This isn't just a matter of what words we choose; it emphasizes that to advance understanding of the 'topic' (by coordinating the *activity*) we need to identify many 'projects' with aims achievable in 3-4 years.*

With this in mind, we can think of your proposal in Section 3 as needing to be specialised to specific projects. (See Sect. 5.3.3.) Formulating achievable goals for these (sub)-projects is surely a creative task in itself. But, for example, Jean Bacon has one such project already running, involving traffic in Cambridge. I don't know the project as well as I should, but I believe it involves knitting together at least two of the GC themes: Experience (what do citizens and the City Council actually want?) and Design (what event-based model can express alternative designs to achieve this experience?)

One can think of this kind of project as helping to formulate an appropriate dynamic model, rather than as presupposing an already perfect such model.

A different project (prompted by Jon Crowcroft) could involve the comparison of two different design choices for a specific application: 'distributed control' (each car has its say) with 'centralised' control (the highway makes all the decisions). To do this comparison one still has to postulate a model in which both designs can be expressed; so the project can be regarded proposing and testing the Model as well as identifying the differences in Experience provided by the two designs.

Other projects can involve theoretical aspects of such models: how to express designs (in some mix of logics, process calculi, differential equations, and languages based on these); how to analyse the state-space of a design (by pencil and paper, or by model-checking) to

ensure that some requirements are met; how all of this can be done stochastically; etc. These theoretical aims pertain to ALL ubicomp systems of course; but theories, like engineering principles. designs, get established through specific application.

5.3.3 Coordinating a Foothill Activity

In GC2/4 there is debate about how a foothill activity can be coordinated, and woven into the coordination of the whole GC activity. This is hard; and presumably it's even harder to do between two GCs! You already address this in 6.4.2 where you expect '20 to 30 groups' to be enlisted. The big question is: how do they interact? I'm sure it depends, as you are hinting, on gathering a steering group who really believe in the coordination as much as in their own specific research. This group ought to be more or less equally represent the two GCs. What will not work is to try to do this top-down! It follows that, like democracy, it sometimes cannot be done at all. But we can continue to try.

5.3.4 Specific Comments on DB's Early Draft of This Paper

- *At the start of 1.4 you introduce domain models as abstracting reality. I think one of our main problems is that they have to model 'future' reality, or future possible realities. That's where we have not the luxury of a natural science – where the reality is not (or is only very slowly) modified by the model!*
- *This raises a question-mark about the Dogma (Sect. 2.1), first bullet, where you say "First one must establish a ... domain theory". In GC2/4 we imagine that the model (or theory) will only be arrived at by the research; so it's one of the ultimate aims of the GC, not a first step.*

5.3.5 Comments, III of III

You will find the specific comments addressed in [9]:

6 Project Management

6.1 Self-funding

This project frame proposal does not imply central funding. That is, each partner must find own funding. Each partners is expected to contribute at least 6 person months of research per year — and typically 6-18 such months per year.

6.2 A Patchwork of Overlapping, Individualistic Contributions

Challenges # 1.–# 10. indicate rather clearly that there is room for individual groups to contribute to just one of them. It is then hoped, through "gentle coercion and persuasion" to get these or other individual groups interested in "filling the gaps".

> **Challenge # 11. Management:** It is indeed a management challenge to get as many groups to work in order to "fill" the programme, so that all challenges (# 1.–# 10.) are taken care of, and it is indeed a management challenge to make sure that the patchwork hangs together, that is, to fullfull challenge # 0.

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6.3 Project Plan

The project plan can only be very loose: This project is not centrally funded, is a research project with very many open issues, requires individuals of widely different skills that must be "fused", etcetera.

The best we can suggest at this time is for the reader to take a look at Fig. 1 and at our sketch "milestone" plan, Sect. 6.5.

6.4 Resource Requirements

The project is characterised by a diversity of issues, from domains via requirements to software; from integration and composition of medium to large scale specifications expressed in many "styles", transitions from domain via requirements to software design specfications, the establishment of formal relations (for these transitions), and the verification of annotated code. This calls for many groups to contribute to the project, each with their specialty, some working already on other foothill projects of either of the two underlying grand challenges.

We therefore expect a number from 20 to 30 groups to be enlisted in this project for it to succeed.

Each such group may be from one person working at least half time to several (3–4) such persons. And for typically 3–4 years.

It is expected to hold an annual "Verified Software for Ubiquitous Computing" workshop — probably as part of some event of the two underlying Grand Challenges. It is deemed mandatory that each group participate three or four consecutive times in these workshops.

6.5 "Milestones"

These are the short, medium and long term goals to be reached:

- **Short Term Goals:** Summer 2007

  The gathering of at least some 20 or more reasonably committed and reasonably strong research individuals (groups), the holding of a kick-off workshop, and hence the start of the project.

- **Medium Term Goals:**

  In chronological order we list one set of "deliverables", one could call them the "on the path from domains to verified software" deliverables:

  - **Domain Specifications** 2008–...
  - **First Set of 1–2 Requirements** 2009–...
  - **Next Set of 4–5 Requirements** 2010–...
  - **Requirements to Domain Relations** 2011–...
  - **First Set of 1–2 Software Designs** 2012–...
  - **Next Set of 4–5 Software Designs** 2013–...
  - **Software Design to Requirements Relations** 2013–...
  - **Program Annotations to Requirements and Domain Relations** 2015–...
  - **First Set of 1–2 Verified Program Code** 2016–...

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  - **Next Set of 4–5 Verified Program Code** 2018–...

We then list supporting theory "milestones". These are more trhought of as individual contributions (i.e., papers) that are produced in a hopefully steady flow:

  - **Domain Theories** 2009–...
  - **Requirements Theories** 2011–...
  - **Integration Theories** 2009–...
  - **Compositionality Theories** 2009–...
  - **Theories of Ubuiquity** 2009–...
  - **Theories of Proof Score/Scripts &c.** 2009–...

- **Long Term Goals:**
  - **Verified Software for Automated Highways** 2020–...

6.6 Project Board and Management

Obvious one must have "such a thing": board, project leader, etc. Tony Hoare's and Robin Milner's comments in Sects. 5.2.3 and 5.3.3 are all relevant in this context.

7 Conclusion

We have sketched a foothill project within the two grand challenges of 'VSTTE: Verified Software, Theories, Tools and Experiments', and 'Ubiquitous Computing', the latter specifically in the context of 'Automated Highways'. Both of the two grand challenges had set somewhat different scopes and spans for their expected activities. The current proposal attempts to bring the two together on "one hat".

8 Acknowledgements

Discussions over the last six months with (in chronological order) Tony Hoare, Cliff Jones, Michael Jackson, Kokichi Futatsugi and Robin Milner are much appreciated.

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