DISCRETE EVENT MODELLING METHODOLOGY FOR INTELLIGENT TRANSPORT SYSTEMS

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SUMMARY

Motivated by work on Electronic Fee Collection, we formulate a general simulation concept to evaluate the performance of Intelligent Transport Systems, and introduce the virtual sensor concept as a concept for sensor system modelling. We demand that interaction between elements of the system is well defined, and that their state changes at pre-definable time intervals. As a result we can model the total system as a discrete event model.

INTRODUCTION

Modelling and simulation has extensively been used in the design of intelligent transport systems such as aeroplane-, car- and drug design etcetera. All examples have in common the fact that the basic understanding of how to design these systems comes from well understood first principles, stemming from physics or chemistry, such as for example in Computer Fluid Dynamics, Computer Finite Element Mechanics, Computer Electro Magnetics and Computer Molecular Dynamics.

Other example cases can be encountered where modelling and simulation are applied to the design of systems where the computer is the main- or an integral part of the total system and where the computer reacts on stimuli from the outside world. They can be found, among others, in the design of Consumer Electronics, in traffic management systems and in various other types of embedded systems. In those situations computer systems are applied to increase system intelligence as well as to monitor, control and improve system behaviour.

We have developed a modelling and simulation approach, and realised a software environment to perform these simulations for Electronic Fee Collection (1,2). The environment is in use by the industry for technical evaluation studies. As a result of this specific work we have formulated a general simulation concept for Intelligent Transport Systems (ITS) that include subsystems for detection, communication, registration and classification. We will introduce the virtual sensor concept the modelling of such sensor systems. We demand that interaction between elements of the system is well defined, and that their state changes at pre-definable time intervals. As a result we can model the total system as a discrete event model.

This paper describes the general simulation concept and aims at initiating a discussion on the possibilities and limitations of the modelling and simulation techniques applied.

MODELLING METHODOLOGY FOR ITS

Characteristics of Intelligent Transport Systems

Due to heavy road congestion in the Netherlands, especially in the western part around the major cities (Amsterdam, The Hague, Rotterdam, Utrecht) the Dutch Government has started the Rekeningrijden project (3), intending to implement a system of Electronic Fee Collection with the goal to reduce this congestion. It is foreseen that these systems will have to become operational in the year 2002. The fee collection function should not disturb the normal traffic flow. Therefore, a free flow Automatic Debiting System (ADS) is required.

We have set up the ADS model simulation as follows. First, we apply a small number of hierarchical decompositions of the ADS and use (known) parameterisations of the remaining subsystems to describe their behaviour. The connections between the subsystems and the response of the subsystems to the presence of vehicles are specified, resulting in a model of an ADS. The models are designed to fit in the discrete event paradigm, which means that all subsystems have well-defined state vectors which change, due to external inputs or due to the connections with other members, on pre-definable time stamps. This is an important requirement because in this way the modelling concentrates on the total system design and on coarse-grained modelling. We believe however that this property can characterise a wide class of Intelligent Transport Systems.

We would like to remark that it is vital to this modelling approach, in terms of connecting models of subsystems together in a discrete event model, that the subsystem models are validated and the range of validity of the models is known exactly.

High Level Modelling

To investigate the correct functioning of an ADS, a simulator is used. The tool, called ADSSIM (1), uses a discrete event simulation method and has the structure of a generic toolkit for traffic telematics applications. In this section we will investigate how its concepts can be used for the modelling and simulation of Intelligent Transport Systems. We postulate here that the methodology can be used as a generic simulation concept for systems that can be put in the simulation framework depicted in figure 1.

Environment Modelling and Simulation

Environment Description. Here a description is given what aspects of the environment of the system will be taken into account, in the sense that the environment is described as the source of external stimuli to the system. Based on the environment description, initial hypotheses can be raised what environmental aspects are important for the performance of the system. These hypotheses can be refined during later system analysis. It is also possible to include control parameters in the environment description through the modelling of Monitoring Stimuli. For example, the system manager can monitor the speed of the flow through the system by prescribing a speed limit.

Environment Model. Here high-level modelling is applied to the Environment Description, in order to obtain a formal description of the environment which can be implemented in a simulation. At this level it is decided what aspects of the Environment Description are modelled or neglected.

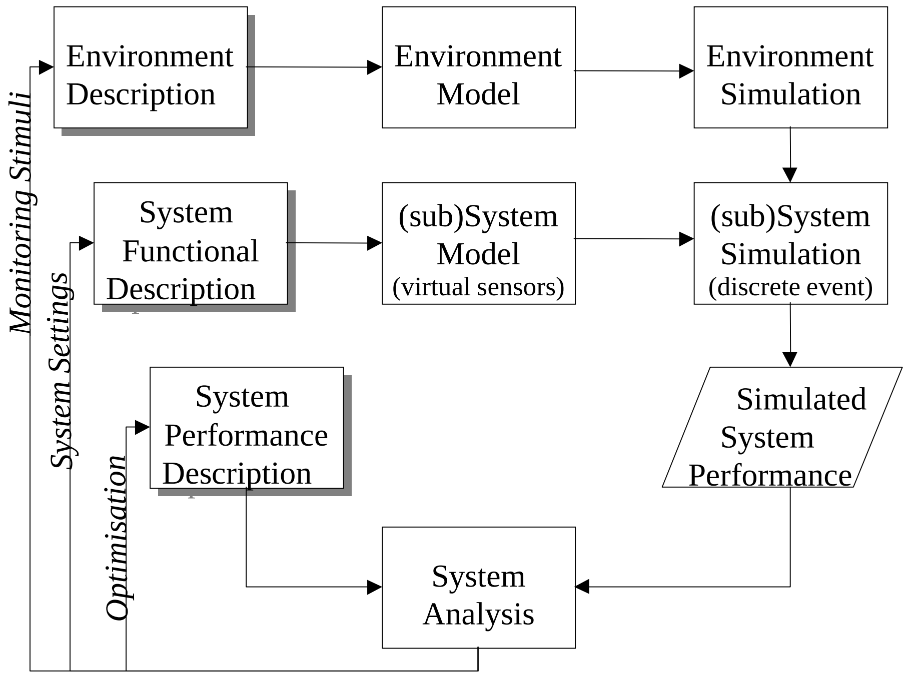

Figure 1: Simulation concept for Intelligent Transport Systems

Environment Simulation. This is a software model of the Environment Model. In our case, the environment simulation produces a sequence of stimuli for the (sub)System Simulation. The following facilities are available in the ADSSIM tool to simulate the environment :

- Road traffic simulation, generating microscopic traffic (vehicles) entering the fee collection zone. The Road Traffic Simulator generates the trajectories of vehicles. The vehicles show different longitudinal and lateral behaviour depending on their state (free flowing or following traffic). Vehicles show different behaviour under different light conditions (day, night), precipitation conditions (wet, dry road) and traffic conditions (flowing or congested traffic).
- Stimuli that influence the behaviour of the system, such as occlusion of a communication sensor in a vehicle by a large other vehicle while communicating with another communication sensor.
- Spontaneous stimuli, allowing the simulation of stimuli that do not fit in any of the previous categories, for example a bird passing under a detection sensor.

<u>*System modelling and simulation*</u>

System Functional Description. Here a description is given of the functioning of the system, including systems settings (e.g. parameters calibrated for an expected work load or priority parameters for a communication protocol) that influence its behaviour. The system settings can possibly be influenced by the system itself, for example the priority parameters may be changed by the system when the intensity of the flow through the system changes. The functional description also includes a geometric description of the system, for example a geometrical description, specifying the static "hardware" configuration of a system, or a network layout description, specifying the nodes and links in a communication network. In any case, the location of sensors and communication subsystems must be defined by using so-called sensitive zones of the sensors, so that the discrete event methodology applied in the

simulation is able to compute the moment when the sensors start and stop receiving stimuli from the environment.
(sub)System Model. High-level modelling is now applied to the System Functional Description, in order to obtain a formal description of the system, which can be implemented in a simulation. The Virtual Sensor formulation, discussed later in this paper is a useful means to establish this. At this level it is decided what aspects of the System Functional Description can be implemented, possibly applying an incremental development of the simulation. Since we consider systems where the computer is an integral part of the system, the modelling of application errors (indicated by the embedded computer) is an important aspect of the (sub)System Model.
(sub)System Simulation (discrete event). This gives the simulated system behaviour, as implemented in the computer simulation. In fact the ADSSIM simulator is basically as a scheduler of events, scheduled either automatically as a result of the environment simulation, or as the result of the functioning of the modelled (sub)System. The tool schedules events from the environment simulation together with events scheduled by the user of the simulator. The following facilities are available in the ADSSIM simulator to perform a discrete event simulation of the system behaviour:

- Entering and leaving the sensitive volumes of sensors (detection sensors, communication sensors, registration sensors).
- Simulation of communication protocol. Since the computer is an integral part of the total system, this facility is important, since it is the way that the computer communicates with other parts of the system or with the outside world. The communication protocol model library of the simulator can support the user in the simulation of a data-communication protocol between Road Side System and On Board Unit. The library functions enable the user to calculate the moment in time when a next step in the protocol is executed in an Automatic Debiting System. The functions make it possible to model medium access control and communication conflicts.

<u>*System Performance Evaluation*</u>
System Performance Description. These descriptions are formulated to quantify the system response in a form of system performance. For example, system performance numbers give a technical or a user view on the system performance, system cost factors a financial view. The performance of the system can be optimised by modifying the performance description as a result of the system analysis.
Simulated System Performance. The simulation of (sub)Systems under stimuli of the environment will result in a System Response (logs and reports), which can be used to analyse the system.
System Analysis. This is a process that compares the Simulated System Performance with the System Performance data. A technical analysis (for example failure mode analysis) can be performed comparing the System Response with the requirements, giving SQFs (System Quality Factors) for the system. An economical analysis (for example a spare parts analysis) can give the total costs associated with technical failures, giving LCCs (Life Cycle Costs) for the system. The system analysis may result in adaptations of the process, in the form of Monitoring Stimuli to the environment, change of System Settings in the System Functional Description and optimisation of System Performance Description, as is shown in figure 1.

The Virtual Sensor model

In this section, we introduce the Virtual Sensor concept as a reference for sensor system modelling. A *Virtual Sensor* is a (real or imagined) combination of a physical sensor with data processing and interpretation software, capable of measuring a parameter. A *Virtual Sensor* is a (conceptual) device of which the output can be modelled in terms of the relevant characterising parameters, and in the outputs of other physical or Virtual Sensors, see figure 2. The Virtual Sensors should be modelled at an appropriate level of abstraction. It must enable a sufficiently accurate characterisation of the total system behaviour. At the same time the abstraction level must keep the interactions between the various Virtual Sensors (relatively) simple, both in statistical and in causal relationships. In a simulated system we have the additional demand that the Virtual Sensor models should be amenable to being *validated*.

For an ADS a *Virtual Sensor* is a component that measures *one* of the parameters of a passing vehicle, for instance the length. The “measurement” may be a single measurement or a composite result of a number of physical measurements. The length of a vehicle may, for instance, be determined by combining the time-stamps of the passage of the front and back of the vehicle (measured by laser curtains) with a measurement of its velocity. The length of a vehicle may also be determining from a single measurement, e.g., by processing a blob in an image. The processing of raw sensor data, too, is to be viewed as a part of the Virtual Sensor, thus modelled in terms of the relevant characterising parameters.

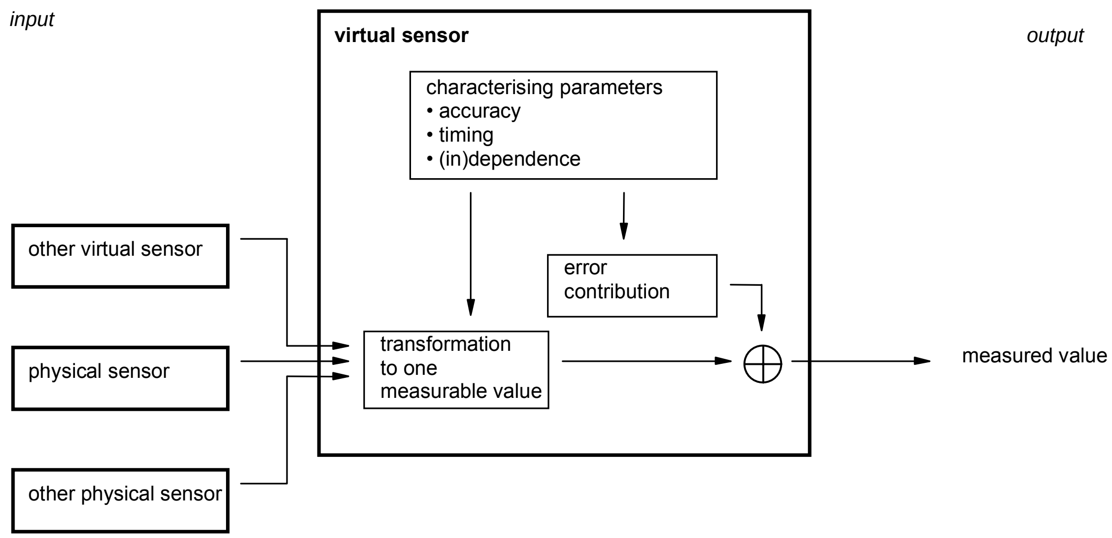

Figure 2: The Virtual Sensor Concept

Different aspects of the behaviour of a Virtual Sensor have to be modelled in order to estimate the output of the sensor at different conditions:

<u>Accuracy.</u> A Virtual Sensor will measure a vehicle parameter h (height) will do so with a limited accuracy. This accuracy has various aspects, all reflected in the distribution of the measured h under similar circumstances, in a large number of trials. There are two reasons for inaccuracy:

- *Sensor noise*, and
- *Variation* of the measured parameters of the vehicles during the trials, also due to environmental noise.

The *variation* is caused by the fact that the available parameters can only characterise certain *ensembles* of vehicles and conditions that are validated. This ensemble will exhibit an inherent spread, which manifests itself as an inaccuracy distribution (error contribution) in the Virtual Sensor output. This distribution can be larger or smaller for the different ensembles, i.e., the inaccuracy distribution is a function of the characterising parameters.

Timing. It is important to know *when* and *where* the data can be known. When is the measured parameter available and at what temporal rate does it change significantly? A higher level of abstraction implies modelling at a lower rate of change.

(In)dependence. Sometimes the output of a Virtual Sensor is not directly related to the passage of a single vehicle. It is also possible that a sensor gives multiple outputs for a single value (for instance when a shadow of a vehicle is identified as a separate vehicle). Further, it is possible that the Virtual Sensor gives only one result for two passages (for instance when in the sensitive volume two vehicles are merged, which result in a single measurement of the length). To model the behaviour of the Virtual Sensor in the latter case means that one has to model the correlation between the measurement of a parameter of one vehicle and the measurement of another vehicle.

Validation. A simulation should give a realistic representation of the modelled system, at the desired level of evaluation accuracy for each environment condition simulated. This implies that all elements in the simulation should be validated as indeed representing the real system at the chosen abstraction level.

Although not strictly necessary, it is desirable to choose the level of abstraction such that the parameters at that level are fairly independent, so that their interactions can be modelled in a simple way. This is important for the validation of the models (since one does not need to take their interdependence into account) and also for the number of cases that have to be evaluated separately in the simulator. Virtual sensors will thus preferably be chosen in a way that makes their interdependencies, *both in statistics and in timing*, simple and measurable

A possible realisation of the concept for ITS

The above concept can be applied to many types of Intelligent Transport Systems. In order to make effective use of the methodology, the following elements must be available in the system:

- Sensing technology, which can be modelled using the described Virtual Sensor methodology,
- Discrete events, occurring at specific moments in time,
- Communication between the computer embedded system and objects entering the system, using some kind of communication protocol,
- Actions (e.g. fee collection by the system) or measures (e.g. speed control of the flow through the system) performed by the system to model the purpose of the system.

In such cases effective use can be made of the ADSSIM modelling methodology and possibly also of the ADSSIM simulation environment.

SIMULATION ENVIRONMENT

In the Dutch Rekeningrijden evaluation project (3) it was necessary to implement several, different ADS models. We provided a mechanism for this. The user provides a configuration file, containing the geometry of the ADS, and the event handling routines. These routines, which are written in C, are linked with the ADS simulator through the model interface. They contain the parameterisations of the subsystems and all the logic to connect subsystems, mapped to events, with each other (see figure 3).
The Weather and Traffic modules in the evaluation framework represent the Environment Simulation mentioned previously in this paper; the modules of the ADS simulator represent the (discrete event) (sub)System Simulation and the System Analysis, while the sets described as "Unjustified Registration" … "Free Ride" indicate the System Quality Factors (SQFs) that result from the System Analysis.

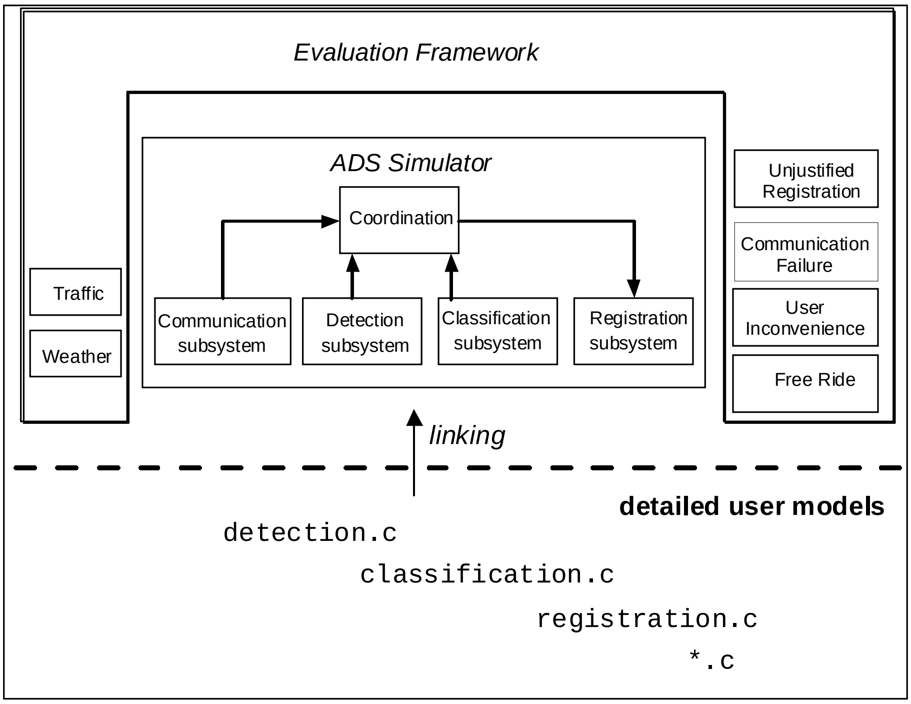

Figure 3: Software design of ADSSIM simulator

The facilities of the ADSSIM simulator are described in (4). In this paper we only describe along which lines the simulation of the system behaviour is carried out. The evaluation framework receives trajectories of each vehicle and passes them to the ADS simulator. At the correct time the ADS simulator launches the vehicles entering the ADS. Subsequently the ADS simulator calculates at which time the vehicle enters and leaves all sensitive zones, which are defined, in the configuration file, and on each of these times schedules events. These events, which are automatically scheduled by the simulator, form the basis to implement the ADS model.

DISCUSSION AND CONCLUSIONS

The modelling and simulation presented in this paper has been used within the Dutch Rekeningrijden project by five vendors in order to demonstrate the feasibility of their ADS system. The industrial end-user community has a growing awareness of the usefulness of simulation as a tool for demonstration and promotion of their ADS concepts. Full-scale evaluations (containing in the order of a million vehicles) can be done in a number of days, depending of course on the complexity of the implemented simulation model and the size of the available computer network.

The next discussion points exist with respect to the presented discrete event methodology:

- The discrete event property is valid as long as the number of hierarchical decompositions remains limited. In other words, the modelling is done on a high level and the granularity of the models must remain comparatively coarse. In case fine granularity is needed in the modelling, it is preferred that such detailed computations are computed "on-line" (without using extra events) to avoid an explosion of the required number of events.
- A case study is performed on the level of granularity for one of the subsystems: the communications part (5). The conclusion of this case study was that an increasing level of modelling detail could change the estimated performance both to the positive as negative side. An increasing level of detail was equivalent with an increase of the used computer resources, but by applying a high level model as worst case assumption, the usage of the detailed model could be reserved for the passages that had a high change of failure. Hereby limiting the used computer resources to an acceptable level.
- An interesting question is if the discrete event property is too strict, or if some elements of the Intelligent Transport Systems should be represented by discrete time models, resulting in a hybrid discrete-time-discrete-event model of the total intelligent transport installation
- Extending the previous question, an interesting aspect of discrete event simulation is also whether it is suitable for Multi-Disciplinary Design purposes, in order to model the interaction between various disciplines while defining an Intelligent Transport System. It is foreseen at the moment that not all disciplines will be amenable for a discrete event formulation, so that such systems will almost by definition use hybrid discrete-time discrete-event models.
- Discrete event simulation is almost by definition a tool with promising design facilities, since only "relevant" events are taken into account in the simulation, and details are only taken into account where needed.

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