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A Hierarchical Model and Implementation Architecture for Road Traffic Control

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***Abstract*— Control of traffic in a network of roads may involve a large number of individual control loops, with various scopes and time scales, some of them working locally, such as traffic signals at a crossing, some of them coordinating a number of local control loops within its scope. In order to organize such a set of control loops, this paper proposes a hierarchical network model which is primarily based on a modularity property of networks. One of the prime applications of this hierarchical model is to derive an implementation architecture for the development of operational control systems, including the necessary hardware and software infrastructure, in order to achieve highly flexible control systems and thereby support the research in road traffic network control. The primary goal of this paper is to list the research issues of this approach.**

I. INTRODUCTION

In most countries, road traffic is the most flexible and most important, but also the most expensive, most polluting and, by far, the most dangerous means of transport [1]. Traffic management is widely used to improve traffic efficiency and safety and to reduce environmental damage. It includes activities such as traffic control, law enforcement, fee collection, travelers information, etc. Traffic control consists of influencing the flow of traffic by means of visual signals. The oldest and most common means of traffic control are the traffic signals at crossings. Currently there are many more control measures, but the vast majority have in common that they operate locally, hardly take the network context into account and therefore work reactively. Proactive operation would require looking into the future, but then it would be necessary to look at a wider part of the network than just the local scope of control. Reducing congestion for instance cannot be done effectively with purely local control, as there is a serious risk that reducing congestion at one location will only shift the problem to some other location in the network.

Among the major challenges in road traffic control is this transition from local, reactive control to network-wide proactive control, which we will denote by *network control*. Network control is in essence the coordination of local measures. It can be argued that other forms of network control are not likely or can be replaced by a set local measures with some form of coordination. As long as traffic control operates through visual signals to drivers, all measures operate essentially locally. What can be added is a coordination layer on top of these local measures. In the future, it may become possible to apply different types of actuators, most likely via wireless data communications to vehicles, but currently there is no legal basis for new types of actuators. Experience, especially with road pricing systems [2], has shown that systems involving interdependent combinations of lawmaking and technology development are long term endeavors. It is safe to assume that visual signals will remain the most important kind of actuators for many years to come, which implies that any network wide control measure can be replaced by local measures, subject to some form of coordination. More about this in section III.

New in this article is the systematic derivation of a hierarchical network model for network control from very general principles together with an implementation architecture for network control systems. Target group is the research community in traffic management and the traffic management systems industry. Goal of this article is not to define the definitive network model and implementation architecture, but rather to demonstrate the architectural approach to network control and to list the research issues in this approach.

II. PROBLEM STATEMENT

The essence of the challenge of developing network control, is a chicken-and-egg problem [3]. In order to find out how to do network control, experiments with real-life traffic are needed. Simulations are useful, but in order to determine how accurate simulation outcomes are, real-life experiments are indispensable. The latter require roadside equipment suitable for network control. Current equipment was not designed with this purpose in mind. Although current equipment can be applied, investments are needed to upgrade this equipment and to install some highly desirable new equipment, for instance traffic cameras that can measure actual travel times. Travel times are an important network-level quantity, the one that drivers are very interested in, but travel times are hard to derive from the traditional local measurements with induction loops. Such investments are high, often prohibitively high if the purpose is only research with an uncertain outcome. In addition, working with existing equipment involves all the problems of legacy systems. Existing equipment features a variety of technologies, as it was installed in various periods in the past and stems from various manufacturers. Nevertheless, in many industrial countries, traffic problems are so severe, that traffic management authorities are sometimes willing to invest and

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to experiment with network control [4] [5], so there is progress in this area, but it is slow.

This chicken-and-egg situation implies a tight connection between traffic engineering and the engineering of computer based systems. It is imperative that any systems development and especially the development and installation of roadside equipment, be such that it will be able to serve a wide variety of different network control applications, many of which still have to be developed. The common approach to this kind of problems is architecture development [6].

In this paper we explore this relationship between network control and IT-systems engineering. First we model network control by means of a hierarchical network model. This might be called the business part of the architecture. Then, from this hierarchical model, we derive the IT-parts of the architecture, to be called the *implementation architecture*. The hierarchical model is derived from basic principles and generic properties of networks. The model can be applied to a variety of aspects of traffic control: not only to control itself, but also to control objectives, to monitoring, especially the monitoring of network quantities, to information exchange between system components, etc.

III. HIERARCHICAL NETWORK MODEL

The hierarchical network model is derived from two starting points: the general feedback control loop and the modularity property of networks. Non-feedback control does play a role in traffic control, but is left out of consideration here. It can be modeled as a degenerate form of feedback control.

A. The control loop

Figure 1 depicts a well-known model of the most basic feedback control setting [7]: there is one target system and there is one control unit.

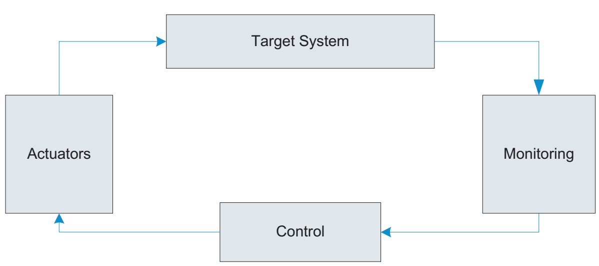

Fig. 1. The feedback control loop

The picture features the most common components of a control loop:

- *Target system*: the system to be controlled, in this case: a network of roads with traffic. The system may be subject to other influences, not controlled by the control unit, but these are not made explicit here. The weather is a typical example of such an external influence in the case of road traffic.
- *Monitoring*: the component that supplies information about the target system. It consists of two parts: the sensors, that collect the raw data from the target system, and a state estimator, that processes the raw data into higher level information. The essence of the monitoring component is that it supplies information about the current state of the system.
- *Control*: the unit that takes the control decisions. It consists of three main parts: the state assessor, the state predictor and the decision maker. The state assessor evaluates the current and/or predicted state according to a number of criteria. In essence the assessor tells the control unit whether the target system is leaving the safe region of the state set. The decision maker then decides what exactly has to be done, what measures have to be taken. The control unit may have other sources of information to base its decisions upon, for instance weather forecasts.
- *Actuators*: The actuators apply the control decision to the target system.

In network control, there are many control units operating simultaneously and effecting each others target system, because traffic moves through the whole of the network and frequently crosses individual control scopes.

Due to the complexity of the target system, the scope of each control unit is limited. Practice shows that the scope is often very limited, for instance just one crossing. The complexity of the target system is already so high in this case, that research on improving traffic signals at a single crossing still continues [8].

Typical for traffic control is that the actuators are discrete whereas the target system itself is a continuous system. This stems from the fact that the effect on traffic is achieved by visual signals to human drivers. Continuously varying actuators do not seem appropriate in this setting.

B. Modularity of subnetworks in a network

A road network consists of *links* (a stretch of road in one driving direction) and two kinds of nodes: *choice points*, where a driver may choose between several roads to continue his trip, and *merge points*, where several roads come together and the traffic streams of these roads are merged. In urban networks, choice points and merge points may coincide, for instance at a crossing of bidirectional streets. In motorway networks, choice and merge points are usually separate. An essential property of networks is that when we consider a subnetwork, as in figure 2, the mutual influence of the subnetwork and the rest of the network goes exclusively through the connecting edges, which results in a finite number of interface points. From the point of view of the subnetwork, the rest of the network can be abstracted to the effects on these interface points.

This principle can be applied recursively [9] [10]: a large network may be split up into a number of subnetworks. Within each subnetwork, this step can be repeated. In this way, a tree structure emerges, that constitutes the hierarchical model for networks. The tree features a number of levels, and at each level, a network of subnetworks. This is illustrated in figure 3 for the European road network. For the purpose of control, countries and national networks are a natural subdivision. Traffic control requires authority, and the nations are the natural units of authority within the European continent. Within a country, the network is divided into a number of regions, under the control of a TMC (traffic management centre). This may be related to provinces but often they are not. For the purpose of traffic control, provinces are often not the most appropriate subdivision. Within the region of a single TMC, attention is not given to all roads and crossings homogeneously, but attention is focussed on a number of areas where traffic is more problematic than at others, such as the belt roads around cities. These areas form the next subdivision. We call them *Focal Areas*. Then finally we come to the lowest level in the tree, the level of links, and choice and merge points.

The number of levels, and especially the number and size of subnetworks within a level, may be subject to regular readjustments, as practice shows. It is an important requirement for the implementation architecture that such readjustments shall be well supported (see below).

Each node in the tree (not to be confused with nodes in the road network) has a parent node, child nodes and, within the same level, peer nodes (with obvious exceptions at top and bottom). This structure can describe several aspects of the network control problem, not only control, but also control objectives, monitoring, information exchange, etc.

IV. CONTROL IN THE HIERARCHICAL MODEL

This section describes how individual control units fit in the hierarchical network model, briefly denoted as *the tree*. A control unit at an arbitrary node in the tree (figure 4) has a parent node, children nodes and peer nodes. It controls its target system by giving instructions to its children, it receives instructions from its parent, and it may exchange requests with its peers. The first we call *vertical* control, the second form *horizontal* control. At the bottom of the tree, there are the typical local control systems such as traffic signals and ramp metering systems. Apart from control requests, peers may also communicate for other purposes, such as plain information exchange. Higher up in the tree, control is more and more a matter of traffic management policy implementation by humans. The levels most interesting for our purposes, the levels that deal with network control and where IT plays an important role, are the Focal Areas level and the TMC level. The initiative for vertical control will usually be with the parent, but it may also be with the child when, for instance, two adjacent control units cannot handle a problem among themselves and have to bring the problem before their common parent or their parents. In the case of two different parents, the same procedure can be applied. The process certainly stops, as there is only one top node.

An important principle within the tree is the principle of *non-overlapping control scopes*. This principle serves the purpose of simplifying the control problem. Overlapping control scopes would be the same as having two captains on board of one vessel. There is a straightforward way of solving overlapping control scopes by refining scopes: the overlap should become a separate scope, and the control units involved in this overlap, should merge into a single unit. This can be done in various ways, some of them generic, while others take into account the details of the control laws involved. A generic way is to assign priorities to the two control units, such that, depending on conditions, only one unit is in force at any moment in time. An example of the second kind is the case of two speed limits, issued by two control units with overlapping control areas. Then, in the overlap, one can apply the minimum of the two speed limits.

The practice in traffic control tells us that scope is not only geographical scope. There may be, for instance, both a speed control system and a fog warning system with an overlap of their control areas. Returning to non-overlapping scopes seems less needed in this case, than it would be with functionally the same control units.

Even in the case of non-overlapping control areas, there is the issue of *consistency* among controls. Each control

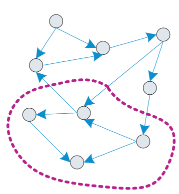

Fig. 2. Modularity of subnetworks

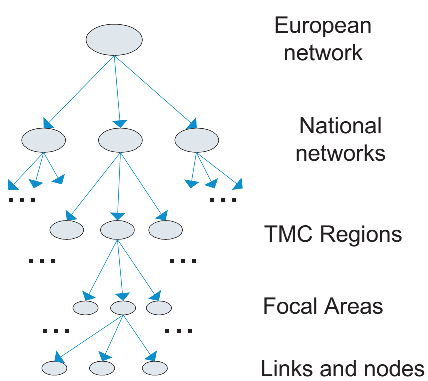

Fig. 3. The Hierarchical Model for the European Road Network

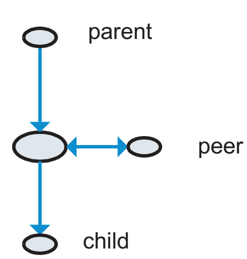

Fig. 4. A node in the Hierarchical Network Model

unit has a certain effect on traffic. This effect is usually not limited to the unit's control area. Different control units may therefore have opposite effects in some part of the network, for some part of traffic. Control measures are themselves dynamic, which means that the same control unit shows different signals to drivers entering the unit's area at different times. Ideally, synergy should be guaranteed for any two active control units, as seen by any driver passing through the respective control areas. In practice, this ideal may come down to a trade-off where a disadvantage for some drivers is acceptable in view of the beneficial effects for many other drivers.

Apart from control itself, other related subjects, such as control objectives per level, and traffic monitoring, can also be modeled by means of the hierarchical model. We illustrate this briefly with the example of monitoring. Monitoring consists of the collection of basic, point based, quantities, such as speeds and flows, and deriving higher level quantities from the lower ones, such as travel times over routes, traffic states in a network and Origin-Destination (OD) matrices. Quantities are clearly related to levels: travel times make little sense for a choice point. Quantities have a natural level in the tree where they fit best. A node in the tree, responsible for determining a certain quantity, will ask more basic data from its children. Sometimes, as in the case of OD-matrices, this may also involve information exchange with peers: what comes in at an entry point of a subnetwork, is what goes out from the neighboring subnetwork at that point and this subnetwork may have information about it. The node will apply the information for its own control purposes and it will transmit the information to its parent. Here too, the initiative for information exchange may not always be with the higher node. If a parent has expressed interest in certain information from its children, the children may take the initiative to transmit this information when it becomes available or when it is updated.

It was stated above that we consider control at a given level as the coordination of control units at the adjacent lower level. If one would skip this lower level, this would cause a strong increase of complexity at the higher level, which would then have to process all the information of the all the control areas in the lower level. In principle any actuator setting at the lower level can also be done by a control unit at the lower level, in the pertinent area. This shows that control is indeed a matter of coordinating control units in the adjacent lower level and that reducing control complexity is an important guiding principle in determining the optimal set of levels.

The tree shows that there is virtually an infinity of ways to assemble control units for traffic control, both at the local and at the network level. In practice, the assemblage is usually not static, but subject to a continual process of adding new controls, merging controls, readjusting control areas, removing controls, etc. Practice shows that the best way of controlling traffic is often dependent on the specific network geometry and traffic characteristics in the area. There is a strong need for guiding principles to find the best (or at least a practical approximation of the best) combination of controls in a given area, in order not to lose track.

V. ARCHITECTURE FOR NETWORK CONTROL

It was mentioned before that an important application of the hierarchical model lies in the derivation of an architecture for network control, including an implementation architecture for the computer based systems for control and monitoring. We briefly show how the hierarchical model can guide the architecture development process.

Architectures are in essence high-level designs [6], with a low level of detail, but considering and relating many more aspects of the subject than is normally done in a detailed design. Although the lack of detail has its limitations, experience shows that architectures help in obtaining a better fit between the business subject (network control in this case) and the IT applications, and they help in pinpointing the important decisions in an envisaged system, the decisions that are expensive to change later on.

A prime requirement for network control systems, is high flexibility, in order to have systems support the research in network control. A second important requirement is that systems shall be able to include legacy components and to be interoperable with legacy control and monitoring systems. The control loop and the tree imply the main aspects of a control system that are to be taken into account in the architecture.

Main architecture components:

- *The Context*: Any control unit is part of a larger assemblage of control units with which it interacts. The context also involves other activities, by various parties, that have some relation to pure traffic control.
- *The Organizational architecture*: Models the parties involved in traffic control, their interests and their behavior. All control objectives stem from some organization that is interested in this objective.
- *The Control architecture*: This is the functional part of the architecture.
- *The Information architecture*: This models the information that is created in and exchanged by the control units. It also models the necessary data abstraction which makes that a single traffic related quantity, such as speed, can be derived from a variety of different measurements (induction loops, cameras, radar, etc.)
- *The Application architecture*: This models a generic, computer based, control unit, apart from the components or aspects treated in other parts of the architecture. This involves an interface for interoperability with other control units.
- *The Sensors and Actuators architecture*: This architecture offers a generic model for sensors showing those parts and aspects that different sensors have in common, in order for a sensor to fit within the control system as a whole and in order to ensure that sensors can be shared by more than one control system. The same for actuators. For sensors, this architecture models the abstraction from sensor to information item. For

actuators this architecture models the abstraction from visual signal to control effect. This allows a desired effect on traffic, such as a speed reduction, to be implemented with a variety of different visual signals from various kinds of actuators. In this way, many details of sensors and actuators can be kept hidden from the higher architectural layers.

- *The Technical Infrastructure architecture*: This part models the platforms and data communications networks needed for the implementation of traffic control systems. This architecture involves a middleware model [11] for communication within and between control units, supporting the various forms of push and pull communication identified in the previous section. Push communication means that the initiative to the information exchange lies with the producer of the information, whereas pull communication means that the initiative lies with the consumer of the information.

Quite some experience is already available in the field of architecture development for traffic management and related applications [12] [13]. This is part of the field of ITS (Intelligent Transportation Systems). One may expect that existing architectures for traffic control offer a useful starting point for the network control architecture envisaged here.

VI. RESEARCH ISSUES

We summarize the main research issues identified in previous sections.

- *The hierarchical network model*: How complete is the hierarchical model for network control? Can every existing and future control system be fitted into this model?
- *Network Control*: Is every form of network control above the purely local level, always a form of coordinating lower level control units? Or are other forms of network control imaginable?
- *Control Complexity*: How can we measure the complexity of a control unit and how can this measure guide us in determining an optimal or a workable set of levels in a given road network?
- *Consistency of control units*: How to ensure consistency of control units, both within one level and between levels?
- *Guiding principles*: What are effective guiding principles for the development of network control and how do we find them?
- *Network control architecture*: Which existing architecture in the area of traffic control or traffic management would be a good starting point for the network control architecture and what has to be changed or added?
- *Interoperability standards*: Which interoperability standards are needed to ensure interoperability between control systems from different manufacturers? What aspects of control systems have to be standardized to ensure this?

VII. CONCLUDING REMARKS AND FURTHER RESEARCH

The hierarchical model seems to be a very natural way to structure network control problems, and to help in deriving implementation architectures for monitoring and control systems for networks. The interoperability standards would address a very serious problem in the current market for control systems, in which interoperability of products from different manufacturers is the exception rather than the rule. Successful standardization in this area would be a tremendous step forward in the area of traffic control.

VIII. ACKNOWLEDGMENTS

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