Time-bounded Adaptation for Automotive System Software

Serena Fritsch, Aline Senart

Distributed Systems Group
Trinity College Dublin
Dublin, Ireland
fritschs, senarta@cs.tcd.ie

Douglas C. Schmidt

Institute for Software Integrated Systems (ISIS)
Vanderbilt University
Terrace Place, USA
d.schmidt@vanderbilt.edu

Siobhán Clarke
Lero
Distributed Systems Group
Trinity College Dublin
Dublin, Ireland
sclarke@cs.tcd.ie

ABSTRACT

Software is increasingly deployed in vehicles as demand for new functionality increases and cheaper and more powerful hardware becomes available. Likewise, emerging wireless communication protocols allow the integration of new software into vehicles, thereby enabling time-bounded adaptive response to changes that occur in mobile environments. Examples of time-bounded adaptation include adaptive cruise control and the dynamic integration of location-aware services within fixed time bounds.

This paper provides three contributions to the study of time-bounded adaptation for automotive system software. First, we categorise automotive systems with respect to requirements for dynamic software adaptation. Second, we define a taxonomy that captures various dimensions of dynamic adaptation in emerging automotive system software. Third, we use this taxonomy to analyse existing research projects in the automotive domain. Our analysis shows that although time-bounded synchronisation of applications and data is a key requirement for next-generation automotive systems, it is not adequately covered by existing work. [1]

Categories and Subject Descriptors

D11 [**Software/Software Engineering**]: Software Architectures; A1 [**Introductory and Survey**]: Survey

General Terms

Documentation

Keywords

Dynamic Adaptation, Automotive Software Systems, Taxonomy

1. INTRODUCTION

The amount and complexity of automotive software has risen dramatically during the past several decades due to decreasing hardware costs, increasing computing/communication power, and growing demand for new vehicle functionality [15]. Modern vehicles contain over 2,000 individual functions, such as airbag control software, X-by wire applications, and infotainment applications [35]. Software has thus become a dominant factor of the automotive industry [6].

Moreover, emerging wireless communication protocols, *e.g.,* dedicated short range communications (DSRC) [4], enable vehicles to interact with each other and with their surrounding environment. These protocols allow the integration of applications and data into vehicles from vehicular and/or infrastructure networks. Automotive services and systems that were traditionally vehicle-centric are thus becoming inter-vehicle and vehicle-to-infrastructure-centric [9].

Next-generation automotive systems (*e.g.,* computer-assisted vehicles) will run in highly dynamic environments (*e.g.,* inter-vehicle coordination) and will need to adapt their behaviour at runtime (*e.g.,* in response to frequent changes in their environment). Possible adaptations include the dynamic allocation of resources, adaptation of (multimedia) content, and the adaptation of software structure and functionality. Resource adaptation is concerned with the proactive allocation of resources for better quality of service (QoS) [13], whereas content adaptation involves transforming content to adapt to device capabilities (*e.g.,* transcoding of content based on display resolution and processing capabilities [21]). Software adaptation, in contrast, involves the dynamic introduction of software modules and reconfiguration of software architectures, as well as changing parameters that affect automotive system software [23].

In general, the goal of software adaptation is to make automotive systems more evolvable, intelligent, and useful to drivers [11]. For example, future driver information systems can dynamically integrate software modules, such as a location- and price-aware lodging discovery service based on driver preferences. Other software adaptation use cases include reconfiguring a vehicle control system to operate through partial failures.

In automotive systems, software adaptations must often be time-bounded since stale information could trigger improper driver reactions. For example, a driver information system should update a display within a bounded time to ensure drivers are not informed about traffic jams that no

longer exist. Likewise, adaptations should minimise software update times to ensure that software applications and data are fully integrated into vehicles before they are used.

Next-generation automotive systems differ in their need for dynamic adaptation support. This paper identifies the software adaptation requirements of the following four classes of automotive systems: (1) **vehicle-centric systems**, whose dynamic adaptation needs are limited, *e.g.*, handling error conditions [37], (2) **driver information systems**, which require the dynamic adaptation of content, as well as periodic update of vehicle software to better reflect the current environmental conditions, (3) **cooperative driving systems**, which adapt their behaviour according to the surrounding vehicles and road conditions, and (4) **vehicular sharing systems**, which use the processing power and data transmission of multiple vehicles to perform distributed computations.

After discussing the software adaptation requirements of these four classes of systems we define a taxonomy that characterises various dimensions of their dynamic adaptation, including binding time, constraints and type of adaptation, timeliness requirements, and adaptation trigger. We then use this taxonomy to classify existing projects and reveal gaps in this work that require additional research on time-bounded integration of software modules.

The remainder of this paper is organised as follows: Section 2 motivates software adaptation in automotive systems via a managed highway scenario; Section 3 summarises prior efforts to classify adaptive automotive systems; Section 4 identifies four automotive system classes and their characteristics with regards to dynamic adaptation; Section 5 defines a taxonomy of the identified characteristics; Section 6 categorises existing research projects in terms of this taxonomy; and Section 7 presents concluding remarks and identifies promising areas of research.

2. MOTIVATING EXAMPLE FOR TIME-- BOUNDED ADAPTATION

Managed highway scenario. To make our software adaptation discussions concrete, consider the following example from the domain of intelligent lane reservation system for managed highways. The goal of a managed highway is to reduce congestion, enable vehicles to maintain safe speeds, and allow emergency vehicles to arrive safely and faster at accidents [33]. One way to schedule and enforce vehicle QoS on a managed highway is to allow drivers to reserve lanes "slots." Moreover, lanes can be partitioned (*e.g.*, low vs. high priority QoS) and can be priced differently. For example, travellers could reserve slots on low priority lanes cheaper than travellers willing to pay extra for slots in a high priority lane that allow them to drive faster and reach their destination sooner.

In this managed highway scenario, vehicles indicate their destination and potential constraints or desires on their way points. To ensure proper admission control, vehicles wait in a queueing lane for their reserved slot to become available before entering the highway (*c.f.*, Figure 1). A highway entrance assistance system (*e.g.*, a tollgate) uses short-range communication and relays between queued vehicles to ensure proper software versions and necessary hardware are installed before allowing vehicles to enter the highway. Example software could include warning applications, secure
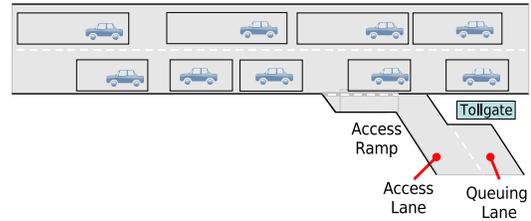

Figure 1: Managed Highway Scenario

payment algorithms, and infotainment applications, such as hotel and restaurant finder or car-to-car gaming; hardware could include road condition and vehicle motion sensors and sufficiently powerful on-board computers.

Software adaptation mechanisms. The managed highway scenario described above motivates the need for various software adaptation mechanisms. For example, the assistance system could use an adaptation scheduling mechanism to determine which modules to download and integrate dynamically into vehicles based on global and/or local adaptation policies. These policies can specify the actions (*e.g.*, integration, upgrade, downgrade or deinstallation of software modules) to execute on the vehicle, as well as the properties with which (*e.g.*, version numbers or priorities) these modules must comply.

One adaptation policy involves the integration of all high-priority modules, *e.g.*, warning and security applications have higher priorities than infotainment applications and hence must be integrated before a vehicle enters the highway, whereas lower-priority modules are optional. Another adaptation policy involves the dynamic update of an existing module to a newer version that is located at the assistance system, *e.g.*, updating a secure payment algorithm. Yet other adaptation policies include the downgrading and de-installation of modules due to expirations of licences or the change of vehicle ownership [3].

The adaption process itself is time-bounded since the decision process of which modules to download and integrate and the actual download of the modules itself must be executed before the vehicle can enter the highway. These adaptation policies can be influenced by the available memory on a vehicle platform, module interdependencies, and versioning of the modules. For example, all necessary high-priority modules may not be downloadable due to timing or memory constraints, in which case a new time slot may be needed for the vehicle. Likewise, the integration of a secure payment algorithm might trigger an additional integration of digital signature algorithms and secure communication modules that increase the overall adaptation time and might cause an overrun on the overall time bound.

3. RELATED WORK ON CLASSIFICATION OF ADAPTIVE AUTOMOTIVE SYSTEMS

Relatively little prior work has classified software for automotive systems and existing classifications focus mainly on embedded systems. For example, Karjalainen classified embedded control systems into six categories, ranging from microcontrollers to special purpose control systems [18]. Each taxonomy category is identified by eight characteristic groups,

e.g., hardware architecture and processor capabilities.

Many automotive systems have stringent real-time requirements that can be classified according to their time constraints, *i.e.*, process execution behaviour, timing constraints, and degree of timeliness that they provide [5]. This classification focuses largely on developing integrated schedulers. Other classifications target coarse-grained distributed systems and their characteristics [34]. These characteristics are based on an explicit model of the time constraints as a *path* (the so-called path-based paradigm) and comprise granularity, triggering causes, and classes of data streams.

Dynamic adaptation of general (*i.e.*, non-automotive) software systems is discussed extensively in the literature. An overview is presented in [23], which focuses on compositional adaptation (*i.e.*, reconfiguring the software architecture itself) and classifies projects with regards to their support of compositional adaptation. This taxonomy comprises three dimensions: (1) where to compose, (2) the point in time of composition, and (3) the techniques used. The authors also highlight challenges, such as assurance and decision making, that an adaptation technique must consider.

Aksit and Choukair summarise approaches for deploying and dynamically adapting applications and software platforms [1]. They distinguish between approaches that deal with the dynamic reconfiguration of component architectures (*i.e.*, introduction and deletion of components) and dynamic adaptability (*i.e.*, the fast adaptation of application behaviour without reconfiguration). They list many technical challenges and solutions (such as maintaining application consistency) to address both approaches.

Although time-bounded adaptation is key to automotive system software, this topic is largely absent from existing surveys and taxonomies. The remainder of this paper therefore presents a taxonomy of adaptive automotive systems with regards to time-bounded adaptation and compares this taxonomy with existing research projects.

4. CLASSIFICATION OF ADAPTATION REQUIREMENTS FOR AUTOMOTIVE SYSTEMS

This section presents the results of an extensive domain analysis of existing and emerging automotive systems aimed at classifying these systems in terms of their level of support for—and characteristics of—dynamic adaptation.

4.1 Vehicle-centric Systems

Vehicle-centric systems assist in the control of a vehicle's behaviour, such as braking or steering. This category contains all safety-critical systems, such as electronic braking systems and X-By-Wire [10]. These systems have stringent safety and reliability requirements since they directly or indirectly affect vehicle behaviour.

In the case of a component failure, safety critical functionality must continue to operate. One way to ensure continued operation is to downgrade a system configuration to a fail-safe state while disabling non-critical functionality [37]. For example, critical functionality, such as a vehicle dynamics controller, can be degraded to a less sophisticated version, whereas climate control can be disabled. In this context, adaptation can be viewed as an error handling mechanism.

All component variants should exist at design time to ensure validity and safety of overall system behaviour. Adapta-

tion should then choose a suitable configuration at runtime. Since components can have different importance levels the decision process may need to take their priorities into account, *i.e.*, the adaptation of the vehicle dynamics controller should be performed before disabling the climate control.

Adaptation timeliness is also important since adaptations should execute quickly to ensure the safe application operation, *e.g.*, disabling climate control in a best-effort time bound. Safety-critical applications may even require adaptation within hard real-time bounds, *e.g.*, downgrading the vehicle dynamics controller within milli-seconds.

4.2 Driver Information Systems

Driver information systems provide information about the vehicle's surrounding environment and the vehicle itself, using internal and external sources. This category comprises a wide range of applications, including navigation guidance, warning about approaching emergency vehicles, and providing information about the vehicle's state. We categorise these systems into the three following sub-classes:

- **In-vehicle entertainment systems**, which provide passengers with audio and video data obtained from other vehicles (*e.g.*, via DSRC [4])) or the infrastructure (*e.g.*, via 802.11p [22] or GSM [29]). Due to the instability of connections in vehicular *ad hoc* networks and the heterogeneity of in-vehicle entertainment systems, different data resolutions are needed to suit device and network capabilities [21]. In this context, adaptation is concerned with changing the video data resolution and modifying compression rates of audio and video data based on current network conditions.

- **Warning applications**, which expand a driver's horizon by providing information about future hazardous road conditions, erratic drivers, and prioritised vehicles (such as emergency vehicles). These systems use information obtained from internal sensors, such as engine temperature sensors, as well as information obtained from other vehicles or the infrastructure, such as the number of neighbouring cars or current weather conditions. Since these systems execute in a mobile environment, information changes continuously, so applications must adapt the displayed information dynamically to accurately reflect environmental conditions. In this context, adaptation involves executing actions depending on the current situation.

- **Travel information systems**, which perform navigation tasks, such as helping drivers locate optimal routes. This category also includes other services, such as hotel, restaurant, and parking space locators. These services are location-based and display information based on vehicle geographic location. Like warning applications, the software execution in these systems is affected directly by the external environment. In this context, adaptation involves the change of software parameters, by using either rule-based approaches or the Strategy pattern [12].

Future driver information systems will communicate with the transportation infrastructure and other vehicles to dynamically integrate new features into vehicles or update older features. For example, at a national border crossing specific types of modules could be installed in driver assistance systems of all vehicles to display additional information about the current country, *e.g.*, maximum allowed speed and specific road signs. In this context, adaptation involves structural and functional software changes that users can trigger

explicitly (*e.g.*, when connected to a 3G network) or implicitly (*e.g.*, by communication between other vehicles and the transportation infrastructure).

Most software adaptations in driver information systems should execute in bounded time to ensure the validity of the information. Adaptations may also depend on priorities between various systems. In the case of software integration, memory constraints and inter-dependencies between modules should be considered.

4.3 Cooperative Driving Systems

Cooperative driving systems require vehicle-to-vehicle and vehicle-to-infrastructure coordination. Examples include adaptive cruise control, platooning, and adaptive steering. Whenever a system parameter changes, such as the distance to the leading car, cooperative driver systems must react accordingly, *e.g.*, by accelerating or braking. Adaptive cruise control involves maintaining a safe time-headway distance between vehicles to ensure emergency braking does not cause collisions between cars. The headway calculation system adapts a vehicle's headway by accounting for changed environmental conditions, vehicle dynamics, and safety considerations [17].

In this context, adaptation involves changing behavioural parameters of a single car to ensure the coordinated behaviour of the group of vehicles to which it belongs. The behaviours of the collaborating vehicles should respond to constraints imposed from other vehicles and from the environment (such as the weather) [16]. This type of adaptation is considered *semi-dynamic* since the system adjusts its behaviour (*i.e.,* the actions to take) by changing system parameters (*e.g.*, the longitudinal control is determined by the distance and the time gap to the next vehicle).

4.4 Vehicular Sharing Systems

Vehicular sharing systems distribute data or computations on vehicles and are comprised of inter-vehicle sharing systems. For example, an environmentally-conscious vehicular sharing system could measure the aggregate carbon footprint of a road in real-time using distributed vehicle computing resources. If the footprint reached a critical threshold, vehicles could adapt their behaviour to reduce the pollution level, *e.g.*, by switching off their climatisation system, reducing speed, or shutting down engines in traffic congestion. In this context, a vehicular network serves as a closed-loop control system, where disseminated messages trigger a corresponding response.

Data can also be distributed and shared amongst vehicles. In this context, the vehicular network can be viewed as a sensing and relaying network, *e.g.*, delivering audio or video data to passengers on long journeys. These types of systems implement resource adaptation, *e.g.*, they provide facilities for monitoring and controlling dynamic resource usage of activities within a system [13].

5. A TAXONOMY OF AUTOMOTIVE SYSTEM ADAPTATIONS

Based on an extensive literature survey we defined a taxonomy that divides the dynamic adaptation requirements of automotive systems into five *dimensions*: (1) binding time, (2) adaptation timeliness requirements, (3) adaptation type, (4) adaptation constraints, and (5) adaptation trigger. Each

dimension can take a finite number of values, which we refer to as *characteristics*.

This section uses Kiviat diagrams [20] to (1) visualise the different dimensions of our taxonomy and their possible characteristics and (2) depict the adaptation requirements of the four classes of automotive systems presented in Section 4.

5.1 Taxonomy Dimensions

5.1.1 Binding Time

Binding time is defined as the point in time when the adaptive behaviour is composed with the business logic of an application [23]. *Static binding time* is used when all forms of adaptability are hardwired with the application, *i.e.*, all possible configurations and resource allocations are determined at design time of the application. A change in the adaptive behaviour triggers application reengineering and recompilation.

In *semi-dynamic adaptations*, all possible configurations of an application are determined at design-time. Depending on the current situation, however, a configuration can be dynamically chosen at runtime. *Dynamic binding* is the most flexible approach since it allows the introduction and alteration of software modules and the reconfiguration of the existing software architecture during runtime without stopping/restarting the application.

5.1.2 Type of Adaptation

The type of adaptation defines what is being adapted. *Resource adaptation* dynamically allocates resources based on current conditions. *Content adaptation* determines how to adapt content to better suit device and network capabilities.

Software adaptation is a category that comprises *parameter adaptation*, *functional adaptation*, and *structural adaptation*. *Parameter adaptation* involves modifying variable values that determine program behaviour. *Functional adaptation* allows application interfaces to remain constant and changes only implementations, *e.g.*, updating of an existing software module to a newer version. *Structural adaptation* changes the actual architectural parts of an application, *e.g.*, by replicating objects or introducing new software modules.

5.1.3 Timeliness Requirements

The timeliness requirements of an adaptation characterise the time constraints under which the adaptation is executed. *Hard real-time constraints* require the execution of adaptation within a firm execution deadline. Adaptations executed under *soft real-time constraints* minimise the adaptation execution and blackout time (which is the time the application is unavailable due to state transfer and reconfiguration). *Unbounded adaptations* are executed without any time bounds.

5.1.4 Constraints of Adaptation

This dimension comprises the various constraints that might affect an adaptation. *Memory constraints* impose a limit on the size of software modules that can be integrated, which is particularly relevant in automotive embedded systems. *Priorities* between modules imply an ordering of adaptations since high-priority modules should be adapted before low-priority modules. Likewise, *dependencies* between software

modules can affect adaptation since adapting one module can trigger an update of other modules.

5.1.5 Adaptation Trigger

These characteristics describe what triggers an adaptation. *Internal triggers* occur inside the system itself, *e.g.*, due to the occurrence of a fault. External triggers, such as *vehicle-to-infrastructure* or *vehicle-to-vehicle*, are based on external information, either obtained by sensors or communication events with other vehicles or the infrastructure.

5.2 Automotive Systems Diagrams

We use Kiviat diagrams [20] to visually present the requirements of the four automotive system classes on adaptation. Dimensions of the taxonomy represent axes of the Kiviat diagrams and characteristics of the dimensions represent the set of differentiating values. The characteristics are ordered by flexibility, from the least flexible characteristic to the most flexible one.

There is no containment priority between the characteristics of a dimension in a Kiviat diagram, *i.e.*, the outermost characteristic does not automatically include the other ones. Since each class has different requirements, they all exhibit different Kiviat profiles and can therefore be compared easily. These diagrams also allow developers of automotive software to visually map the characteristics of their applications to one of the diagrams, which helps identify dynamic adaptation requirements.

Below, we present the representations in Kiviat diagrams of the four classes of automotive systems from Section 4 and describe their corresponding characteristics in terms of the taxonomy dimensions from Section 5.1. If a resulting diagram supports more than one characteristic in a dimension, the outermost characteristic defines the diagram.

5.2.1 Vehicle-Centric Systems

Figure 2 depicts the Kiviat diagram for vehicle-centric systems. These systems require functional adaptation (*e.g.*,
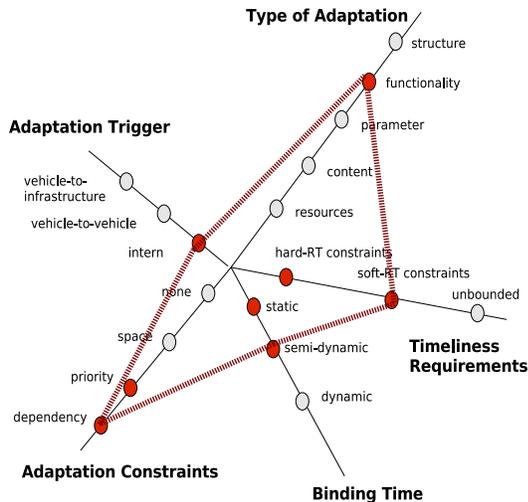

Figure 2: Kiviat Diagram of Vehicle-Centric Systems

downgrading and switching off functionality when a fault occurs), so the adaptation trigger is internal. Moreover, since

these systems are safety-critical, a static or semi-dynamic approach for dynamic adaptation is appropriate and adaptation actions should be executed within bounded time. Priorities and dependencies between modules affect adaptation in these systems.

5.2.2 Driver Information Systems

Since driver information systems comprise a wide range of applications, we divided them with regards to their adaptation type. In-vehicle entertainment systems support content adaptation and the Kiviat diagram for these systems is shown in Figure 3. Since the resulting actions are deter-
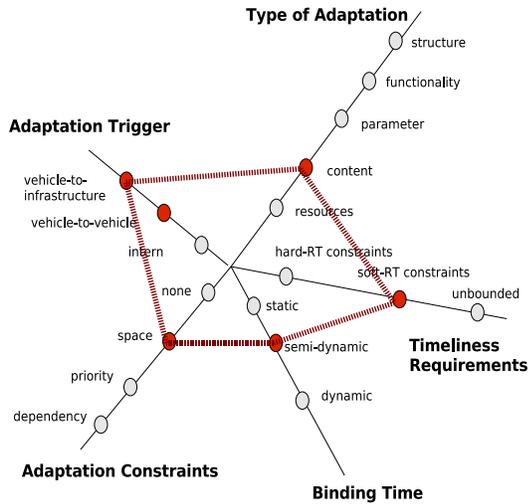

Figure 3: Kiviat Diagram of In-Vehicle Entertainment Systems

mined at design-time of a system (*e.g.*, using event-condition-action rules) the adaptation is semi-dynamic. The execution time of the adaptation should be minimised to ensure the freshness of the displayed information. Adaptation is constrained by the available capabilities of the display device and current network conditions.

Warning applications and travel information systems support the whole range of software adaptation, *i.e.*, adaptation of parameters and also the integration of new services from the infrastructure and other vehicles. The profile of these systems is depicted in Figure 4. This adaptation can be triggered internally by drivers, as well as by inter-vehicle or vehicle-infrastructure communication as software modules are downloaded and integrated via communication links. The binding time of this adaptation is dynamic since new configurations are determined during system runtime. The duration of the adaptation should be executed in soft real-time, *i.e.*, best effort adaptation within time bounds. Adaptation itself can be influenced by the available memory space on the vehicle's software platform. Dependencies between modules and priorities can also influence the scheduling and determination of which and how modules are integrated into the system.

5.2.3 Cooperative Driving Systems

The Kiviat diagram of cooperate driving systems is depicted in Figure 5. This adaptation concerns the change of parameters, such as speed, acceleration, and distance. It can be triggered by inter-vehicle and vehicle-to-infrastructure communication and the internal sensing of the current state of the vehicle.

In cooperative driving systems, actions are determined *a priori* since they may have safety-critical effects on the adaptation. Hence, the binding time is semi-dynamic or even
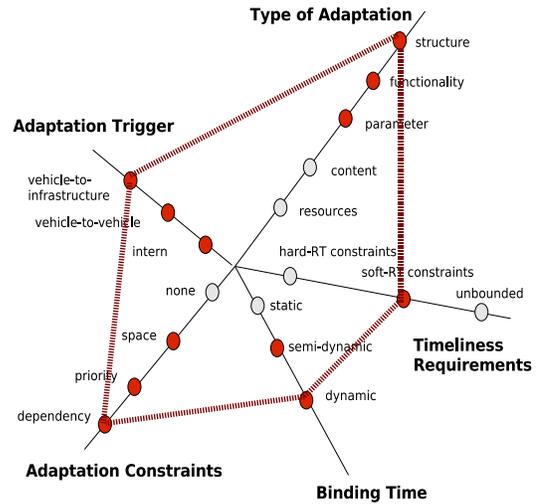

Figure 4: Kiviat Diagram of Warning Applications and Travel Information Systems
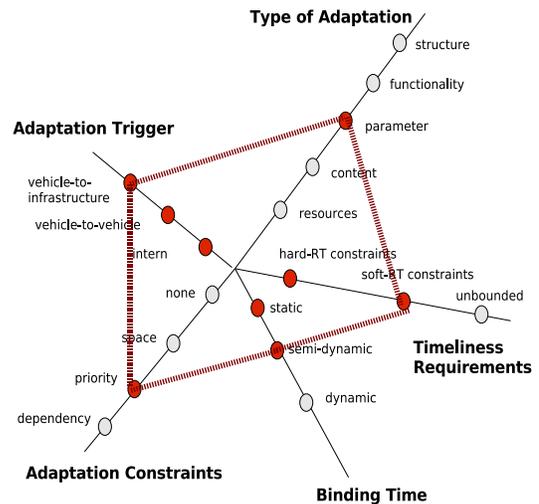

Figure 5: Kiviat Diagram of Cooperative Driving Systems

static. All adaptations should therefore execute within a bounded amount of time and are at least soft real-time constrained. In addition to coordination constraints, adaptation can be affected by priorities of triggered actions, *e.g.*, longitudinal control of a vehicle should be adapted before lane change control to avoid rear-end collisions.

5.2.4 Vehicular Sharing Systems

Figure 6 presents the Kiviat diagram of vehicular sharing networks. These systems require dynamic allocation of
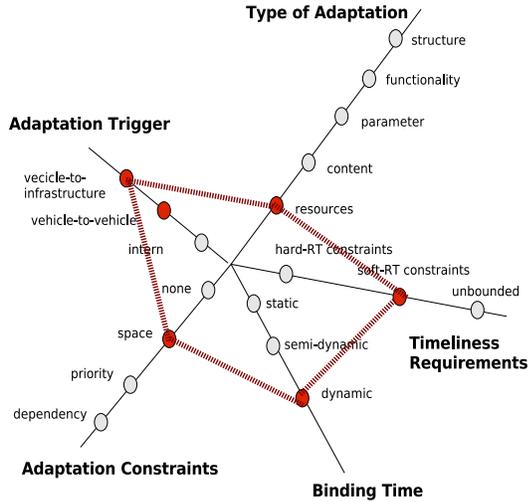

Figure 6: Kiviat Diagram of Vehicular Sharing Systems

resources (such as load balancing and membership mechanisms) since the underlying topology of the network changes continuously. Adaptations are triggered by messages received from other vehicles or from the infrastructure itself.

The binding time of adaptations for vehicular sharing systems is dynamic since new memberships and data or computational loads are dependent on the current status of the network. The nodes in these systems are mobile, so these adaptations should be performed within stringent time bounds. Resource constraints (such as available memory, computational power and bandwidth) impose constraints on the adaptation decision process.

6. APPLYING THE TAXONOMY TO CLASSIFY EXISTING PROJECTS

This section investigates existing research projects and maps them to our taxonomy from Section 5. For each automotive system class described in Section 4, we identified a research project that supports the most suited approach and use Kiviat diagrams to show their degree of adaptation support. We also discuss gaps in these projects with regards to their support of time-bounded dynamic software adaptation.

6.1 Vehicle-Centric Systems

The MARS [37] research project investigates dynamic reconfiguration in embedded automotive systems, *e.g.*, vehicle stability control systems. The approach supports dynamic

adaptation at different levels, from coarse-grained reconfiguration of service providers at the system level to fine-grained configuration of behaviour variants. The Kiviat diagram for this system is shown in Figure 7. The adaptation itself
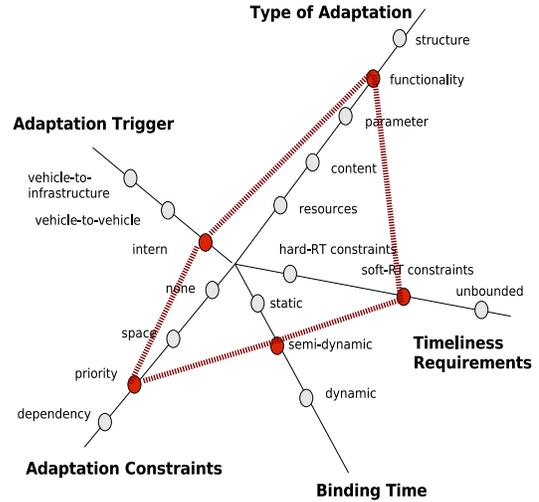

Figure 7: Kiviat Diagram of Mars

is triggered by faults occurring during runtime of the system. MARS handles inter-dependencies between software modules by explicitly modelling and analysing all possible configurations statically at design time of the system. This approach focuses on developing the analysis and modelling techniques for dynamic adaptation, however, rather than developing further adaptation techniques.

The Dynamically Self-Configuring Automotive Systems (DySCAS) [3] project focuses on self-configurable embedded vehicle control systems that are based on existing middleware technologies and feedback control theories. In addition to structural and parameter adaptations, DySCAS supports closed reconfiguration, *i.e.*, graceful degradation in the presence of component failures. DySCAS is based on policies for achieving the self-management of the system. Policy reasoning includes the selection of the most appropriate reconfiguration in terms of priorities and urgency level. Space constraints can also be specified inside policies. The DySCAS project is still in an early stage, however, so no empirical results are yet available.

6.2 Driver Information Systems

Various driver assistance systems are available, including navigation guidance and value-added location based services, as well as safety-enhancing applications, such as emergency vehicle and road warning applications [28].

TrafficView defines protocols and algorithms for the dissemination of information about vehicles on the road [24]. The system provides a dynamic view of the road traffic to help drivers in difficult conditions. The graphical user interface periodically displays all validated data sets, *i.e.*, data that is neither conflicting nor outdated. Adaptation here involves updating the display, *e.g.*, when a change in the validated data sets happens. It is triggered when messages from other vehicles are received. TrafficView only supports static binding time, however, and does not mention any consideration of constraints, such as dependencies.

The Safe speed and safe distance (Saspence) project is designed to provide suggestions of the proper velocity and headway based on the current driving conditions [2]. The project uses internal sensors, such as long- and short-range radar, as well as information obtained from the infrastructure and other vehicles, such as localisation and speed limits. Saspence dynamically adapts its warning suggestions based on the current deduced situation. The system follows a three-layered approach with (1) sensors providing input data, (2) specific algorithms processing the sensor information, and (3) human-machine-interfaces forwarding the warning messages to the driver. The algorithm processing should be executed within soft real-time bounds since otherwise vehicle safety cannot be ensured. This project, however, is still defining functional requirements.

The content adaptation of in-vehicle entertainment systems can be adopted from more general approaches, such as [21], which uses a decision engine to adapt content to fit the current capabilities of the device and network. This engine considers the user's preferences and devices' capabilities, provided in the format of the W3C Composite Capabilities/Preference Profile [19]. Based on the current network conditions and device capabilities, the content is transformed accordingly, *e.g.,* reduction of colour, scale of images, and use of various transcoding mechanisms.

Driver information systems not only handle adaptation of multimedia content, but also support software adaptation. Future use-cases for these systems require the dynamic integration of software into running systems. Application developers for these systems can leverage automotive middleware systems, such as AUTOSAR [27] and OSGI [31], that encapsulate the heterogeneity of computing platforms and communication protocols. These systems support the dynamic integration and reconfiguration of software.

For example, DynamicCon builds upon OSA+ [36], which is a scalable middleware for distributed real-time and embedded systems that support the dynamic deletion, addition, and replacement of services. It minimises application blackout time by allowing state transfer while the old service is still running. Their approach assumes, however, that the software being integrated or updated is locally available and hence they do not consider fully dynamic adaptation as required by this class of systems. Its Kiviat diagram is shown in Figure 8.

The OSGI platform [31] provides a Java-based service platform that supports the remote installation, update, and lifecycle management of Java based applications. In this sense, the platform supports fully dynamic adaptation of application components. The OSGI platform, however, only supports the adaptation of Java-based applications and hence does not support the integration or reconfiguration of heterogeneous software modules.

Fully dynamic adaptation is also supported by application and data synchronisation systems that support the remote integration and update of existing software and data. Platform-dependent approaches, such as Active Sync [25] and LDAP content synchronisation [30], support the synchronisation of information between devices. These approaches, however, only support data synchronisation, *e.g.*, Active Sync synchronises personal information (PIM) and LDAP maintains a copy of a fragment of the directory tree.

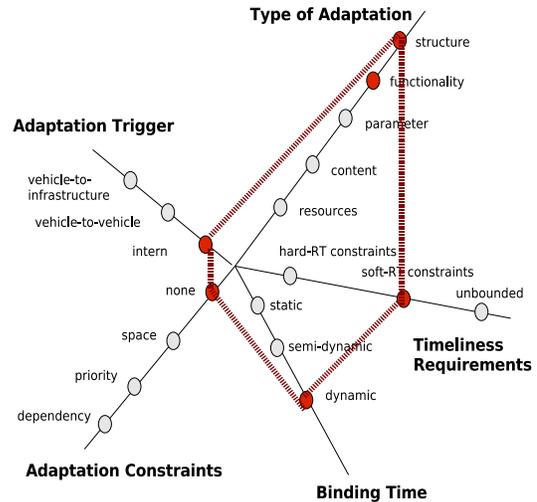SyncML [32] is a platform-independent information synchronisation standard that supports the integration and up-

Figure 8: **Kiviat Diagram of OSA+**

date of data, as well as software applications and firmware. It uses XML to specify the messages exchanged between clients and servers in the synchronisation protocol. It also provides multiple synchronisation modes, *e.g.*, oneway client- or server-side synchronisation and twoway client/server synchronisation.

Current approaches for synchronising data and software binaries, however, lack support for time-bounded adaptation and do not address other adaptation constraints, such as memory, module inter-dependencies, and priorities.

6.3 Cooperative Driving Systems

The Auto21 project is investigating many ways of cooperative driving for fully autonomous vehicles [26]. The authors propose a three-layered architecture to realise decentralised coordination of (autonomous) vehicles [16]. The lowest layer senses the state of a vehicle and is responsible for a vehicle's behaviour. The upper layers, management and traffic control, determine the movement of each vehicle under the cooperative driving constraints.

Adaptation is executed on the longitudinal and change lane actuators, based on information obtained from the traffic and management layer. The longitudinal actuator uses either distance or time-based information to change a vehicle's speed, whereas the change lane actuator follows a pre-defined lane function. The behaviour of both actuators is pre-determined and consists of static rules. The overall adaptation is executed within soft real-time constraints. Due to adaptation being related to parameter changes, it does not account for any constraints, such as memory or module interdependencies (*c.f.*, Figure 9).

Adaptive cruise control systems can be realised by distance policies [17]. In this approach, vehicles move within a safe distance to the vehicle in front of them to ensure that no collisions occur if that vehicle brakes suddenly. This distance must be adapted continuously to reflect environmental conditions, *e.g.*, icy roads, vehicle dynamics, and safety considerations.

Adaptation in an adaptive cruise control system can be executed by the vehicle control system, which is divided into two parts: (1) the upper level calculates the desired con-
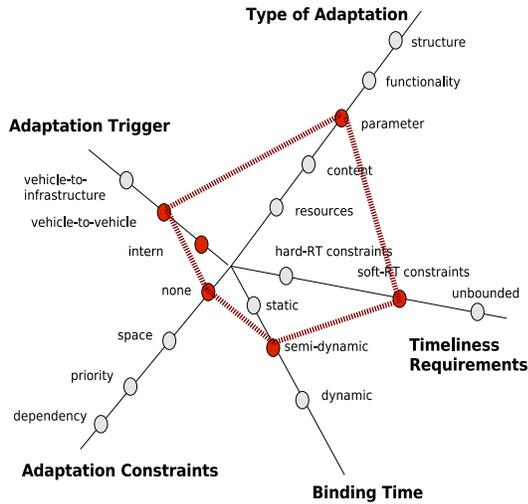
Figure 9: Kiviat Diagram of Auto21

Figure 10: Kiviat Diagram of VMesh

trol effort based on the current conditions and (2) the lower level computes the corresponding throttle commands. The commands execute pre-defined adaptation steps. This approach is local and decentralised, *i.e.*, no information from other vehicles or the environment is considered. Likewise, the adaptation itself is executed without considering any constraints.

6.4 Vehicular Sharing Systems

Vehicles equipped with storage capabilities can act as a store-and-forward mobile router for disseminating data, such as traffic information or audio and video data [7]. For example, next-generation vehicle entertainment systems assume video or audio files can be stored among several vehicles [14]. Depending on their current location, only a subset of these files are accessible for a vehicle and hence a policy framework is needed to predict whether and/or when a file will be available.

The framework leverages existing wireless cellular network infrastructures and is dynamically adapted to the number of vehicles and the available files inside a network cell. This information is continuously monitored and broadcasted to the decision making process residing locally on each vehicle. It does not appear, however, that the adaptation process takes space/time constraints into account.

Within a geographic area, vehicles equipped with processing power can form an *ad hoc* grid computer that can autonomously solve distributed traffic flow control problems, such as lane merging. An example of such a system is VGrid [8], which is a grid computer and is realised by a four-layer protocol architecture in which the grid computing interface serves as a bridge between the applications and the network layers. This interface is responsible for allocating tasks based on the current network topology, *e.g.*, a critical task is replicated to a number of vehicles. A resource management layer controls the access to local resources on the vehicles. Task allocation takes computational time into account since nodes can move out of range before their computations are finished.

VMesh is a vehicular wireless mesh network that serves as a dynamic sensor network, *e.g.*, for monitoring and col-

lecting vehicular emissions [7]. The Kiviat diagram for this approach is shown in Figure 10. A key design challenge in
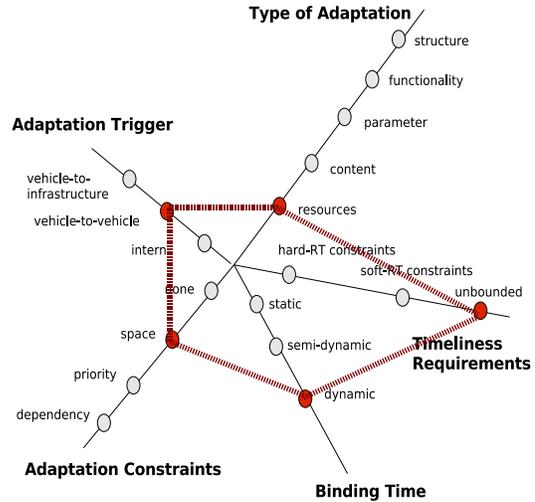
VMesh is determining the penetration rate (*i.e.*, the number of vehicles in the network), which should adapt dynamically to the number of vehicles available. This approach considers memory constraints at nodes to achieve a desired data throughput rate. It does not appear, however, that the adaptation itself supports timeliness, *i.e.*, is executed within a specific time bound.

7. CONCLUDING REMARKS

The prevalence of automotive software—combined with emerging wireless communication protocols—is enabling the dynamic integration of applications and data into vehicles from the infrastructure or other vehicles. These trends, in turn, motivate a new generation of vehicle software that needs to adapt at runtime to respond to changes occurring in highly mobile environments. To ensure the validity of information adaptations must execute in a timely manner.

This paper analysed four classes of automotive systems and identified their software adaptation requirements, including degradation strategies in vehicle-centric systems and dynamically inserting components into software applications. We also defined a taxonomy to characterise various dimensions of dynamic adaptation, including binding time, adaptation type, timeliness requirements, adaptation trigger, and adaptation constraints. Kiviat diagrams were used to represent this taxonomy, compare existing research projects of automotive system software, and categorise existing research projects in the automotive domain in terms of this taxonomy. By comparing these diagrams to the diagrams of our four classes of automotive systems, we identified the following key gaps in existing approaches:

• **Dynamic adaptation in vehicle-centric systems is restricted to at most the dynamic choice of a suitable configuration at runtime**. Since hard real-time systems must ensure the safety and consistency of their execution behaviour at all times, the dynamic insertion and reconfiguration of software modules is traditionally not allowed. Existing approaches, such as MARS and DySCAS (*c.f.*, Sec-

tion 6.1), provide the required runtime adaptation as they change the existing configuration of the system after a fault and additionally can also include new devices and software into vehicle electronic systems at runtime. They do not, however, support time bounds of their adaptations.

• **Driver information systems require not only adaptation of multimedia content, but they also need support for software adaptation**, *e.g.*, dynamic integration of software into a running system. Developers of driver information systems can leverage TrafficView and OSA+, but these approaches assume that the software to integrate or to update is locally available. Saspence and OSGI offer full support for dynamic adaptation and SyncML provides data and software binaries integration, but they do not adapt or update software in time bounds. Moreover, these solutions do not account for time and space constraints as required by driver information systems.

• **Cooperative driving systems need time-bounded coordination between vehicles**. Existing approaches, such as the Auto21 project [26], provide safety critical coordination. They do not, however, support stringent QoS constraints, such as available memory space, for the underlying platform.

• **Vehicular sharing systems need time-bounded allocation of resources and membership management.** These systems must also monitor the space storage and computational power of the vehicles before distributing applications and data between vehicles (*c.f.*, Section 4.4).

To address these gaps in prior work, research is needed on techniques, tools, and platforms for composing automotive software under time constraints. For example, when deciding which modules to integrate or upgrade into vehicle, time and space constraints should be considered. Our future work is therefore defining a domain-specific modelling language and a QoS-enabled middleware execution platform that enables time-bounded composition and deployment of automotive system software.

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8. REFERENCES

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