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MODULARITY BY DISTRIBUTION - THE DEVELOPMENT OF A MOBILE ROBOT PROTOTYPE PLATFORM

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modularity, distribution, modular products, product structure

Abstract

This is a study of a leg-based mobile robot prototype which has been designed based on the specified requirements for both variant leg and variant foot principles. Modular design was emphasised from the very beginning, not only to facilitate variety but also to ease future developments, maintenance, etc. The study deals with the technical issues behind the chosen product structure. Since the product is mechatronic, the structure may be described in terms of mechanical, electronic and software elements. A comparison is also done to commercial products with a similar degree of complexity.

1. Introduction

1.1 Modularity

Modular products normally refer to products that fulfil various overall functions through the combination of distinct building blocks. These building blocks constitute a modular system which should be carefully designed while considering technical, strategic and economical aspects [1, 2]. This is done to meet the customers demand for variety while keeping a rational handling of the product through its life phases. Thus, important ingredients of the modular concept are, compare [3]:

- The modular system should deliver the *variety* in terms of functions and performance that satisfies the customer needs
- The modular system should be based on a high degree of *commonality*, both momentarily and over the time, to satisfy stakeholder demands during the product life phases.
- The modular system should help to reduce the degree of *complexity*, both of the product and of the organisation.

A modular system consists of different types of modules (e.g. common modules, variant modules) and their interfaces. It is frequently stated that this should be designed following certain rules, such as [3, 4, 5]:

- A module should contain what is needed to realise a defined sub-function.
- The modules should be functionally independent (de-coupled).
- The module interfaces should be standardised, simple, stable over time and robust to variation, where the latter implies that modules to some degree should be behaviourally independent.

1.2 Distribution in mechatronic design

Mechatronic products are products that are based on mechanical, electronic and software elements. A basic mechatronic product is built by sensors that gathers information, computers that process information, actuators that act on information and the controlled mechanical parts. Some support systems are needed for energy supply etc., figure 1. In order to design mechatronic products the disciplines of mechanics, electronics, software and control engineering are involved. Thus, mechatronic products are not only complex in due to the number of components or functions, but also due to the need of integration of different disciplines.

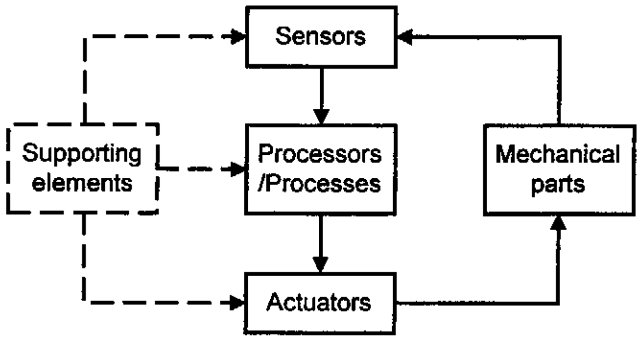

Figure 1. A basic mechatronic system, slightly modified from [6].

In mechatronic product development the complexity could be transferred between the mechanical, electronic and software domains. Furthermore, the functionality and consequently the complexity could be distributed or centralised in the system. This is often discussed in the field of mechatronics; mostly in terms of distributed control. In this context, distribution seem to refer to the co-location of the mechatronic elements, i.e. mechanical, electronic and software/control elements, that are needed for a certain function. Distribution is seen as a mean to achieve integrated units based on different types of elements which fulfil certain functions, de-coupled from the rest of the system's functionality. This facilitate plug-and-play concepts, [6, 7, 8].

2. Objective

The objective of this work is to study aspects of modularity in respect of mechatronic product development. This has been done by following the development of a walking robot at the Royal Institute of Technology (KTH). The work has not focused on the modularisation of an available product, but rather on the development of a conceptually new product while considering modularisation aspects. However, commercial mechatronic products have been studied for comparison.

At KTH, the Centre for Autonomous Systems (CAS) is committed to research in mechatronics, control, vision, etc. The development of mobile autonomous robots is a core activity for the centre, where a special emphasis is put on the development of walking robots since they are supposedly having high capability in difficult terrain. The centre has recently developed a mobile robot platform, initially named Sleipner 3. It is a platform in the meaning that a number of prototype variants and research projects will be generated from a common base. This leg-based vehicle (quadruped) design is based on a few main modules; body, legs and feet. Already from the start two types of legs and two types of feet have been designed in order to evaluate various technologies; electric contra hydraulic actuators and rigid contra flexible feet respectively.

The robot body contains support systems such as on-board power generation, batteries and computers. The legs are built with three degrees of freedom (DOF). The DOFs in the electric legs are realised with three separate electric actuators whereas the DOFs in the hydraulic leg is realised with one separate hydraulic actuator and two actuators that in combination realise the remaining two DOF. The parts are pictured in figure 2a-c.

The development of the robot platform has been conducted with modularity in mind. This in order to facilitate prototype variants, plug-an-play concepts, easy maintenance and future upgrades.

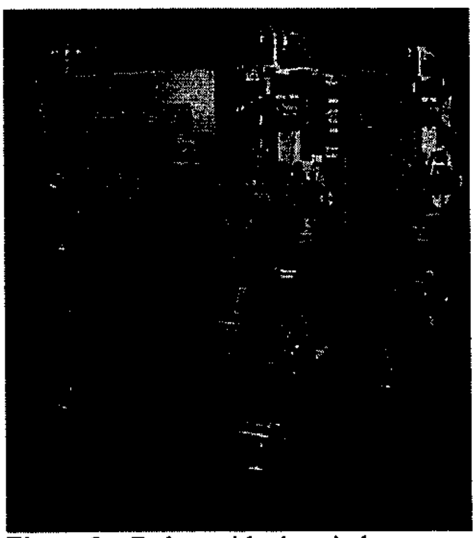

Figure 2a. Robot with electric legs

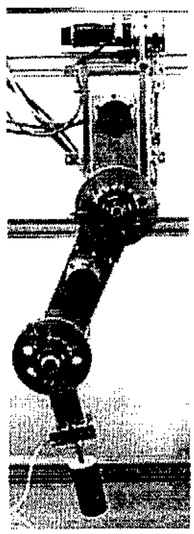

Figure 2b. Electric leg.

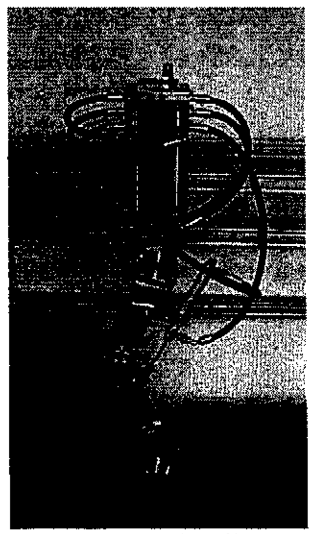

Figure 2c. Hydraulic leg

3. The design; Sleipner 3

3.1 Mechanics, sensors and actuators

Already in the specification it was stated that the robot should be designed with four legs, four feet and a body. Furthermore, the energy source should be on-board. Of course, a number of other demands were put in the specification that relates to performance, ease of usage, ease of maintenance, etc.

Thus, Sleipner 3 was early seen as consisting of a few main modules, i.e. body, legs and feet. Thus, the choice of main modules was intuitive. The decomposition was, however, driven by the specification that required variety and even re-configurability of both feet and legs. Furthermore, from the development point of view it seemed important to divide the development team into smaller groups [9]. It was easy to allocate project groups to the mechanical parts, typically "body", "electric leg", "alternative leg" and "feet", which mainly indicate relations between the groups and the mechanical design. Thus, it also seemed necessary to have functional specialists in groups such as software and hardware. In this situation the problem was to decide what functionality that is needed for a walking robot, the allocation of functions to function carriers (technologies) and the physical location of the function carriers.

Based on simulations it was decided that the usage of four identical legs would ease the development considerably due to reuse of design. Generally, the chosen strategy was to locate the commonality in the body and the variety in legs and feet. This is an obvious approach for the feet since the mechanical principles of the feet will vary. Furthermore, it is specified that the leg actuation principles should vary, which were interpreted as the legs should be varied, i.e. it was decided to locate the actuators on the leg modules. Still, the actuators are not mounted directly at the joints, mainly due to the weight distribution (inertia), which is something that will make modularisation within the leg more complicated. The sensors on the other hand are of obvious reasons mounted directly on the joints.

The pure mechanical parts of the legs have been designed based on preferred size and joint position. The leg development has been done separately for the hydraulic and the electric legs in order to come up with good designs, which resulted in two different concepts using few common components.

3.2 Electronics and control

The most obvious technical reason for distribution of control is the need to reduce cabling in order to reduce weight and increase reliability. Another reason is the need for quick communication in real-time systems. Of course, control cannot be distributed without distribution of electronics. In terms of distributed control there are a number of issues to consider such as, [10]:

- Physical placing of processors within the system.
- Partitioning of control system into schedulable units, e.g. processes and tasks.
- Allocation of processes or tasks to processors.

- Connections of processors and other electronics.
- Execution and communication policies for processors and communication links.

When developing Sleipner 3, these issues were considered. Figure 3a-b show alternatives for the processor structure that have been and still are discussed.

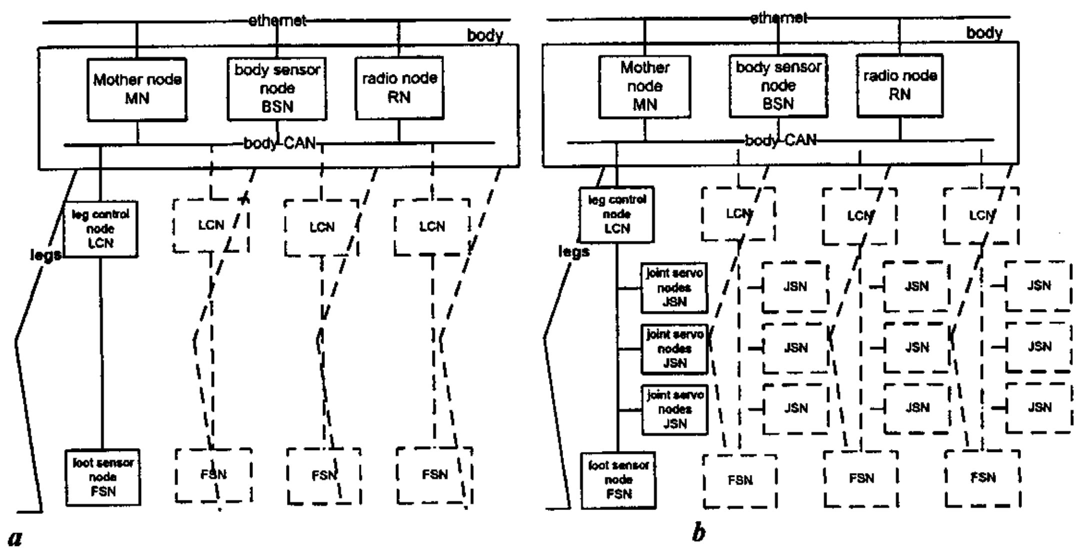

Figure 3. Two levels of distribution for the electronics a) semi-distributed b) fully distributed, [10].

Various alternatives have also been discussed for the control system, where the aim is to make the control of a leg as independent as possible from the control of other legs and the body. The control system must cover functions such as [11]: swinging leg, putting foot down, retracting foot when hitting obstacle, assuring stability, keeping posture, assuring clearance of body, turning robot toward goal, avoiding obstacles, etc. In order to handle the complexity of the control system it must be divided into independent units, [12]. Furthermore, the communication between some of the control elements will be very time critical which may require co-location of elements with time critical relations.

Figure 4 shows how the control system could be arranged in a hierarchy that resembles the hierarchy of the mechanical parts. This hierarchy will not only help to handle the complexity, but it will also facilitate the reuse of the control system at the top levels. Only parts directly related to the actuation technique will be affected when shifting legs, i.e. the portability is increased. In terms of handling variety or re-configurability, only control elements specific for the leg need to be distributed.

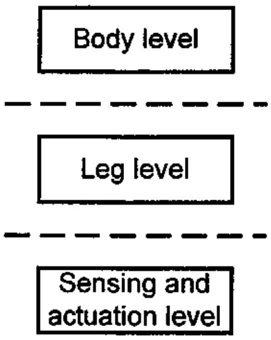

Figure 4. Hierarchical control approach.

3.3 Interfaces

Since this is a new development that will be further developed and changed, some redundant space has been built into the system. This redundant space could for example be equipped with the necessary vision system, gyro, etc. Furthermore, the uncertainty has been handled through flexibility around the interfaces. For example, the electronics are connected to a CAN-bus in the body which makes it easy to add electronic systems at a later stage. However, the bus-technique has not yet been implemented in the legs.
The leg-body interface is electrical and mechanical. This interface have been done so that the geometrical position of the leg may be varied. This in case there is a need to move the mass centre of the body in relation to the legs. Also the foot-leg interface is flexible in terms of space, i.e. the shank is hollow which allows more electronic equipment.

3.4 Discussion

When developing the robot a number of issues have impact on the product structure. Purely technical issues must be considered to realise the needed function and performance of the system. The organisational issues are important since it must be possible to develop the product in an effective way. Moreover, the specified variety must be fulfilled with a limited effort. In this project all these issues have not been fully considered. For example, it may be noted that the two different legs have similar interfaces to body and foot. However, after the initial development it is easily seen that the shank and knee could be modified to form a common unit for both legs, i.e. the legs may be decomposed into modules.

Furthermore, the battery of the robot could serve as an example of how technical issues may have impact on the other issues. In the current concept only one battery is used which serve at least two functions; power supply of electronics and power supply of actuators. In mechatronic systems there is a need to de-couple the power electronics and the control electronics in order to avoid disturbances of the control. The actuators are having a harmful relation to the electronics; the magnetic field from actuators may disturb the electronics and further occasional power peaks from the actuators may leave nothing for the electronics. This may be sorted by shielding but also by a separation of power for electronics and power for actuators. The problem is partly solved by dividing the battery into two batteries, i.e. a division done from a technical point of view, figure 5a-b. At this point it also makes sense to consider the distribution of the actuator battery to the leg, since it is uniquely related to the electric leg. When the leg is changed from electric to hydraulic no redundancy would be left in the body in terms of battery capacity. Furthermore the leg-battery could be optimised for the functionality of the actuators. However, the technical feasibility of moving the battery must be evaluated, especially in terms of the potential effect on the inertia of the leg. The reasoning could then proceed to the generator however that part is strongly related to engine, multiple generators would probably raise the total weight and it will anyhow be needed for both types of legs.

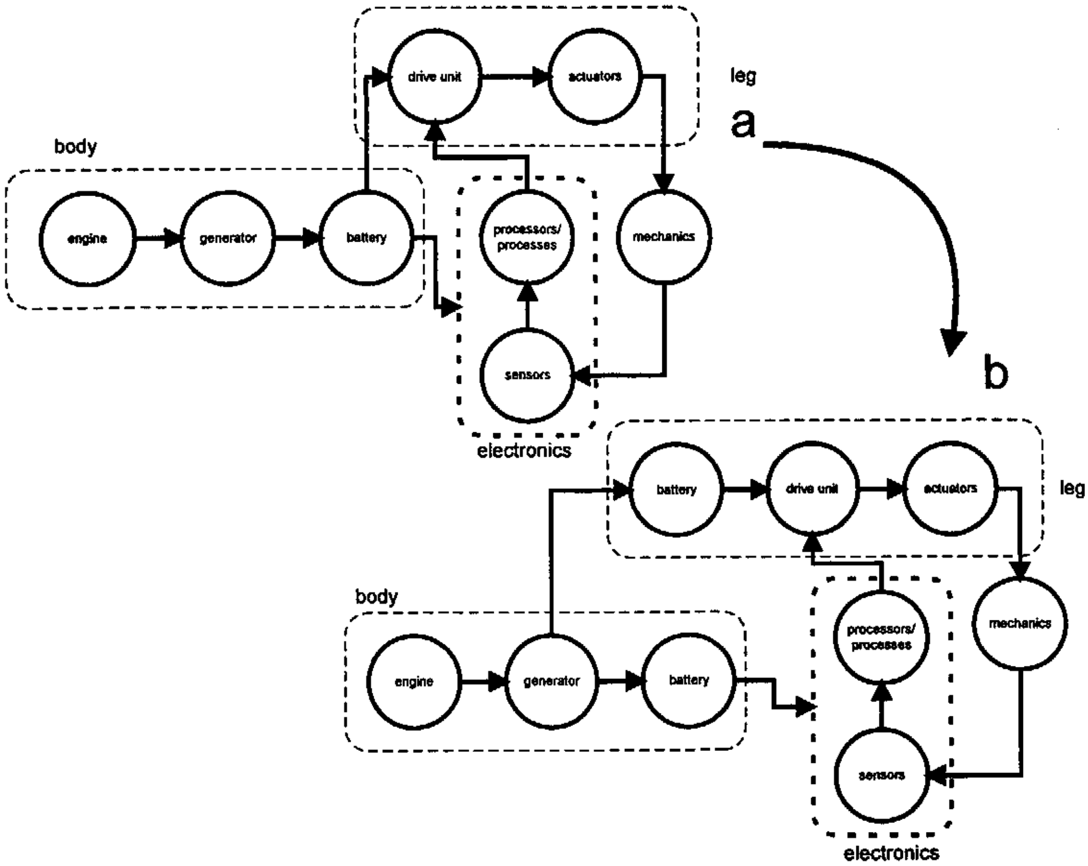

Figure 5a-b. The consequence of splitting the battery of technical reasons may be that it is beneficial to distribute the actuator battery to the leg of variety and re-configuration reasons.

4. Industrial parallels

4.1 General

In conjunction with the development of this initial prototype platform, an industrial pilot-study that widely investigate aspects of modularity has been performed [13]. The industrial study points at issues that relates to the development of Sleipner 3, especially the allocation of various elements of mechatronics in the system. Sleipner 3 is in its early development and thus have not achieved the structure of a mature product. It is therefore interesting to do a comparison by looking at trends, limitations and benefits achieved by the product structure of more mature products.

4.2 ABB Robotics

The six degree of freedom robots from ABB are optimised for its purpose although some variety and module thinking exists. They are developed in relatively small project groups consisting of various disciplines. At ABB the issue of distribution is largely about how the application could be optimised, e.g. the actuators are not always distributed which means that transmissions have to be used. This due to the need for optimisation of performance in respect to the weight distributions effect on inertia. For the cabling it would be very beneficial to distribute the power electronics, drive units, closer to the motors. However, that would lead to weight and heat problems. The control system is designed so that the robot arms follow a trajectory, which means that the movement of joints are optimised as a system. Some degree of modular variety exist but due to the need for optimisation the ABB robot is best compared to one of the legs of Sleipner 3, i.e. the ABB robot can be seen as a module in a production system.

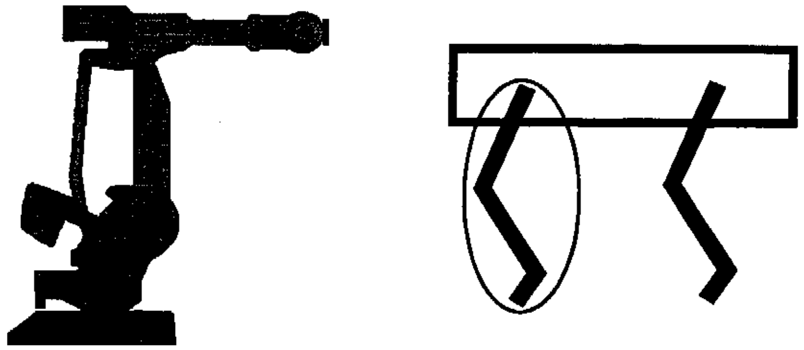

Figure 6. ABB's robot.

4.3 MHU Robotics

The robots at MHU are to a large extent customised from a number of basic modules. Each module handles one or two degrees of freedom in a certain way (electric, pneumatic, rotation, linear). These degrees of freedom may be added to a customised concept, just as a building block system. The actuators are thus distributed to the location of action. The control system and most electrical/electronic elements are centralised. The control system is designed to go from point-to-point which ease the adding of degrees of freedom and changes of geometrical parameters. The MHU system is very flexible but less optimised in terms of behaviour. It could be compared to a design of a walking robot, where the legs are assembled of a number of degrees of freedom. This approach could be used for Sleipner 3 but, for example, its speed would probably go down due to higher leg inertia. The benefit would be the reuse of degrees of freedom for robot arm equipment, etc.

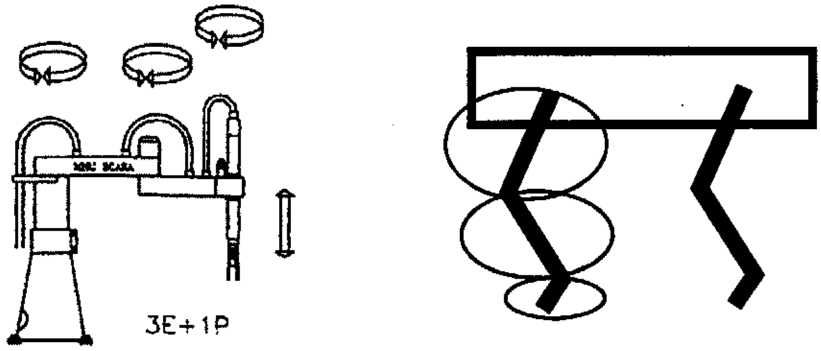

Figure 7. MHU's robot.

4.4 Spectra-Precision

Spectra-Precision has historically used modularity to handle product development and production. However, during the nineties they have extended the modularity to make it possible for the customer to choose functionality as well as upgrade afterwards. At the same time, new functionality is added by making some systems re-configurable. This has been achieved largely by the distribution of processing power from the central processor to a portable computer and other processors in the instrument. The central processors have been changed to a hub function. This type of distribution resembles the distribution in Sleipner 3; it is done to facilitate upgrading or re-configuration by plugging in units that are having well standardised electronic and mechanical interfaces. Legs could be interchanged with wheels as well as cameras, robot arms and sensors easily may be added.

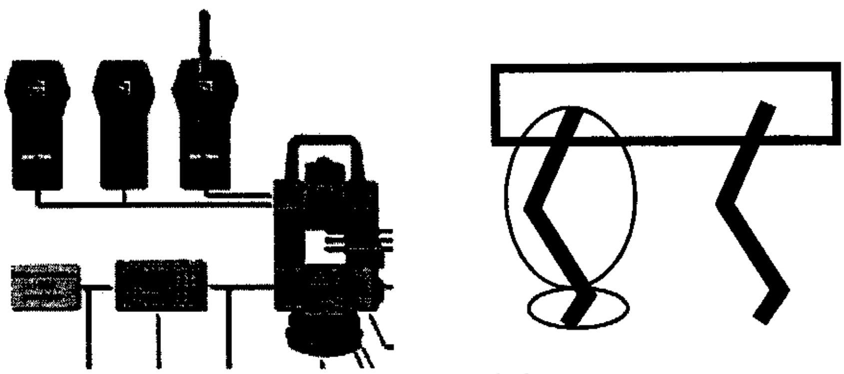

Figure 8. Spectra-Precision's instrument

4.5 Volvo Car

The development at Volvo Car is today divided in cross-functional module teams. These teams develop large chunks of components that are related in various ways, where the assembly process is most notable. Within these modules smaller modules exists to handle the great variety offered to the customer. These organisation and product chunks are crossed by functional systems such as the electrical system. The electrical system has its own development team due to the high complexity and couplings between teams. Since the electronics are distributed, which has been realised through a bus system, the module team for electrical system form a complex interface to the other teams. The main benefit of distribution is the reduced wiring, but also other benefits exist, for example the software loading may be handled more effectively. Volvo has distributed the electronics, but the development of electronics and control is central in contrast to the other parts that is grouped in large development chunks. A similar arrangement seemed necessary for the development of Sleipner 3. There are limitations in this comparison, although it points on the interesting question of how to divide the electrical systems in modules that match the mechanical modules, compare [14].

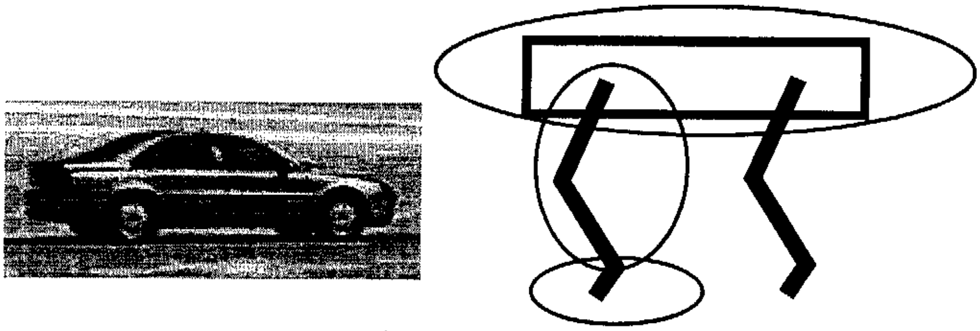

Figure 9. Volvo's car

5. Discussion

During the development of Sleipner 3 the mean to facilitate variety, re-configurability, easy maintenance, etc., has been modularity. Although not outspoken, the striving for functional independency and functional pureness has been a strategy. This by thinking of distribution which in wider sense seem to mean that all elements needed for a main function should be allocated to an integrated physical unit. Thus, distribution could be considered as a mean to achieve modularity by integrated modules.

Distribution is mostly used in the meaning of distributed control, although it could be widened. Thus, in a mechatronic system according figure 1, everything could theoretically be distributed close to where the effect is needed. Naturally, the sensor elements must be distributed and the pure mechanical elements are distributed because they, in a way, constitute the purpose of the system. The other elements are distributed in varying degree depending on the situation, which are ruled by technical, strategic and economical aspects.

Modular mechatronic systems should preferably be based on a de-centralised electrical and control systems since that would give simple mechanical, electrical and communication interfaces. If the module functions are well-defined, it would be possible to divide the organisation accordingly. This, however, seem difficult. The striving for functional pureness by distribution seems applicable for systems like cars and instruments. In more dynamic systems like robots, the need for low inertia makes distribution more difficult. This is obvious for the ABB robots which are optimised in terms of function and performance, while it is less obvious for MHU robots where product flexibility is more pronounced. The parallel could be drawn to Sleipner 3. For static walk the projection of the mass centre is always within the support area, which require three of four legs on ground, whereas for dynamic walk it is not. Static walk would allow more weight distribution than dynamic walking. Thus, static walk could allow larger product flexibility. On the other hand, dynamic walk is probably needed in difficult terrain and to reach required speed. However, to implement dynamic walk, fast responding legs are needed and thus distribution of control may anyhow be required.

Supported by recent literature, the development of Sleipner 3 and industrial cases the problem of *modularity by distribution* may be divided in:

- *Complexity:* Complex products (many functions, disciplines, components, variants etc.) lead to complexity in development, production, distribution, sales, recycling, etc. where this study has focused on development. The division of products is done so that modules could be developed independently although it seems difficult for electronic/control systems to follow the mechanical modules. The complexity problem may be helped by considering some *module drivers* [1]: process/organisation, separate testing, supplier of black box, upgrading, service and recycling.

- *Commonality vs. variety:* The modular system should deliver variety, in terms of functions or performance, enough to satisfy the customer. This should be done while keeping a high degree of commonality. This is a trade-off that must be carefully thought about when developing the products. The commonality vs. variety problem may be helped by considering other *module drivers* [1]: carry over, technical push, product planing, technical specification, styling and common unit.

- *Performance and behaviour*: The lower limits on the specified performance and behaviour must be fulfilled by the product i.e. it forms a constraint. However, between the lower limits and what is technically possible there is a span wherein the function and performance could be traded for other demands. Distribution of a subsystem could be done because it is beneficial from various points of views as well as it could be prevented because it is detrimental from behaviour and performance point of view. These issues must often be evaluated by using sophisticated analysis methods and simulation tools.

These issues may be accounted for by an allocation and validation process suggested by [15]. Distribution is functional allocation driven by all the issues above which must be validated by performance and behaviour simulations. This is probably even more important when dealing with a new design as Sleipner 3.

Modularisation, especially if components may be divided and distributed, could be seen as the evaluation of component relations. The issue could be whether a component is most related to a distinct module or to a cross-modular system in terms of complexity in development, production, etc. The issue could be whether parts are uniquely related to each other or if the relation is common; presently or in the future. Furthermore, the technical relations in artefacts, i.e. the interactions, have frequently been discussed in related literature, e.g. [16, 17].

6. Conclusions

By studying the artefact and the development of Sleipner 3 together with a few industrial parallels some driving and preventing issues for modularity by distribution have been illustrated.

Modular mechatronic systems should preferably be based on a de-centralised electrical and control systems since that would give simple mechanical, electrical and communication interfaces. Distribution may be seen as a way to achieve modularity. However, the degree of distribution may be related to how important the dynamics is for the system is.

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