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Requirements management: An enabler for concurrent engineering in the automotive industry

C. I. V. KERR, R. ROY AND P. J. SACKETT

Defining and agreeing the product requirements is especially important when the design and manufacture of a system is part of an Extended Enterprise. To realise an all inclusive concurrent engineering process, tools for the upstream design activities are needed. In practice, it is often difficult for the companies to have a shared understanding of what needs to be developed and so specifications contain ambiguities in describing the product requirements. This paper clarifies the problem domain in the context of a complex product, designed and manufactured in a pan national Extended Enterprise and serving a highly competitive market. The authors show how the challenge can be addressed through the application of ontology. A model of a requirements management tool is proposed that will allow the various systems and associated levels of a product to be described and then shared through the supply chain. A prototype system is presented and illustrated through a case study from the automotive industry.

1. Introduction

One avenue for realising high quality products, at a competitive cost and at the appropriate time for the market, adopted by several industries especially the automotive sector, is the close and early involvement with the supplier base for product development. Concurrent engineering principles facilitate the design and manufacturing functions of the original equipment manufacturer (OEM) and associated suppliers to conduct varying degrees of their activities in parallel. At the fundamental level it is the product requirements that enable this product development functionality between geographically and culturally distinct organisations. Different organisations operating in a common supply chain, working concurrently during product development must have a shared understanding of the requirements; this is difficult to achieve in practice. Omissions, ambiguities and incorrect assumptions often have to be resolved resulting in increased work effort and cost. This paper will make the case, using the automotive industry as a pertinent example, that a requirements management philosophy is the most fundamental and yet prime factor for enabling concurrent product development between an OEM and their suppliers. Additionally, the paper will present the position that engineering organisations can have a shared understanding of the product requirements through the application of ontology. A case study illustrates the creation and use of ontology and a prototype software tool that harnesses the power of ontology to realise concurrent product development will be presented.

2. The impetus for concurrent engineering in the automotive industry

Many industries are making the move to global sourcing (Esterman and Ishii 2001). Such a tendency is prevalent in the automotive industry. For example Ford, General Motors and DaimlerChrysler are all engaged in this activity – primarily for achieving low prices (Nellore *et al*. 2001). Global sourcing has resulted in a trend of modular supply by the 1st Tier. Although, this trend was initially justified on the basis of cost reduction, Collins *et al*. (1997) report that 'the need for increased speed to market and for new business development' are the driving force. From an OEM standpoint, it is both costly and risky to attempt to provide the level of innovation required by market forces through only internal resources (Hamel *et al*. 1989, Kogut and Zander 1992, Bucklin and Sengupa 1993); suppliers of major modules are playing a greater role during product development (Esterman and Ishii 2001). This is readily apparent in the fact that OEMs are allowing their 1st Tier suppliers greater design responsibilities and involving them at an earlier stage, i.e. during the product definition stage (Chung and Kim 2003). According to Liker *et al*. (1996), this provides the OEM 'access to a wealth of in-depth technical knowledge and innovative capacity'. Just as importantly it also enables the personnel in both organisations to have direct and extensive communication during product development (Clark 1989, Dyer and Ouchi 1993, Liker *et al*. 1996). These trends in the automotive industry provide great impetus for realising an all inclusive concurrent engineering environment. Renault for example are realising the benefits for concurrent engineering, Jordan (2003), with respect to:

- Cutting time and development costs
- Improving design quality
- Mastering the increasing complexity of products

To establish concurrent engineering practices the automotive industry has pioneered implementing digital product development across the supply chain. There has been progress in the harmonisation of CAD systems, the utilisation of simulation tools and the realisation of the digital mock-up for a complete vehicle. PSA Peugeot-Citroen, for example, use their 'Co-Conception' application for digital modelling with their suppliers (Arozamena 2003). However, to have an all inclusive concurrent engineering environment, tools are needed for application in the conceptual product stages and the area of Requirements Management has been overlooked relative to the advances made in digital product development for downstream activities.

3. The importance of product requirements to concurrent engineering

El Wakil (1998) states that there are four pillars upon which the methodology of concurrent engineering rests, namely:

- Organisation
- Communication infrastructure
- Requirements
- Product development

Product design is driven by the product requirements. The needs the product must meet to be a success are the prime factor for initiating the concurrency of work between an OEM and supplier. According to Holmes (1994) 'the essence of concurrent engineering is that all the necessary design inputs are introduced as early as possible, so that the design evolves from a correct basis and separate activities can be carried out in parallel'. Hooks and Farry (2001) state that 'if you have poor requirements, you will end up being either over budget, behind schedule, with an unsatisfactory product, or all three'. The critical input is a clear understanding of the product requirements. If you do not understand what the customer needs then securing a sale and ensuring a profit is likely to be difficult. Specifying and then properly communicating the correct requirements is more crucial when the product development is undertaken by another party, such as the case of a 1st Tier supplier. The OEM is relying on the supplier to not only satisfy them but more importantly their customers – the end users. It is of course the aim of the product development process to fulfil all of the product requirements and to release the product for manufacturing (Naumann *et al.* 2002). In addition to understanding and being clear about the product requirements, they must be communicated to all the parties responsible for development (Svensson and Malmqvist 2001). To enable concurrent engineering there must be greater emphasis on the concept that Sunnersjo *et al.* (2003) refer to as 'requirement-driven'. They state that the product requirements represent the 'voice of the customer' and provide the objectives and constraints for all the phases of the product development process.

4. Problems when working with requirements in practice

The early development phases of many products, including automotive products, are fraught with uncertainty. On OEM-supplier collaboration, Fagerstrom and Johannesson (2001) report that 'many delays in product development projects' are related to inadequate requirements. The production of a set of requirements requires the integration of information from various sources, both internal and external, and in many formats. Individual requirements are added, refined or removed by negotiations, discussions and clarifications. The requirements are traditionally represented within text documents (Svensson and Malmqvist 2001). Effendi *et al.* (2002) recognise that the principal means of communicating requirements is through natural language. However the use of natural language leads to ambiguity in interpretation (Greer *et al.* 2003). When a set of requirements has to be prepared by one organisation, such as an OEM, for another party, such as a supplier, then the scope for ambiguity is even more apparent since the companies do not use a common vocabulary. Such differences in the use of language has been implicitly acknowledged by Renault as an issue during collaborative product development (Jordan 2003). In addition to errors resulting from ambiguities, Hooks and Farry (2001) identify other errors that may be manifested:

- Incorrect facts
- Incorrect assumptions
- Omissions
- Inconsistencies
- Misplacements

DaimlerChrysler have piloted a set of requirement processes, methods and tools for automotive electronic system development (Weber and Weisbrod 2003). They found that engineers often ‘describe specifications in an unstructured way’, this results in an increased communication effort. DaimlerChrysler also identified that their requirements reuse for different variants was ad hoc and implicit since a good requirements specification depended completely on an engineer’s domain expertise (Weber and Weisbrod 2003). The problems in the use of language and vocabulary for product requirements can also be seen in the aerospace industry. Kritsilis (2003) conducted a case study of requirements management at an aeroengine OEM. A principal reason for difficulties in understanding requirements was the use of different terminologies for requirements and their associated definitions. This problem derived from the company's organisational practices where different 'internal businesses' tended to create their own development business processes together with the use of their own jargon for describing features and attributes of the product. On defining product requirements, differences in terminology resulting from different perspectives 'restrict the ability to convey product requirements from customers to designers' (Agouridas *et al*. 2001).

5. A shared understanding of requirements through ontology

According to Toye *et al*. (1993) design occurs as a result of reaching a 'shared understanding' of the design problem, the requirements and the process. Such a shared understanding is reported by Hill *et al.* (2001) to be often manifested by the use of 'similar jargon in documentation'. To enable for product requirements information to be shared in a concurrent engineering context there is the need to address the contextual mismatching of requirements vocabulary and the associated definitions. Ontology offers a solution to this challenge, particularly in the context of a digital environment. 'An ontology is an explicit specification of a conceptualization', (Gruber 1993). A conceptualization is a set of definitions that allows one to construct expressions about some physical domain (Schreiber *et al*. 1995). The explicit specification means that the concepts and relationships of the abstract model are given explicit terms and definitions. This is effectively 'a formal and declarative representation', (Gruber and Olsen 1994, Fikes 1997). Fernandez-Breis and Martinez-Bejar (2000) state that an ontology 'enumerates the concepts that are relevant' in a domain. Neches *et al*. (1991) state that an ontology 'defines the basic terms and relations comprising the vocabulary of a topic area'. Ontology is a 'content theory' (Chandrasekaran *et al*. 1999), it involves defining classes of concepts and the relationships between these classes (Musen 1998). The major benefit of ontology is, as identified by Jasper and Uschold (1999), to promote ‘common understanding’. The goal of ontology is to strive towards ‘consensual knowledge’ through achieving a fixed terminology (Fernandez-Breis and Martinez-Bejar 2002). This involves the convergence of the different language representations to a common format. An ontology can therefore act as a strict work of reference when communicating requirements among both internal departments and external organisations up and down the supply chain.

Using Jasper and Uschold’s (1999) framework for understanding and classifying ontology applications, the Cranfield University electronic requirements management (e-RM) project is developing an ‘ontology as specification’ application for creating and disseminating product requirements (Kerr *et al*. 2004, Roy *et al*. 2004). This application of the concept effectively means that ontologies are created and used for the specification of automotive systems, modules and components. The requirements knowledge encapsulated within an ontology includes product attributes, functions, relations and constraints.

[Insert figure 1 about here]

6. Ontological-based requirements management tool

To realise the benefits of applying ontology for the domain of automotive product requirements, an electronic requirements management (e-RM) framework has been developed. Figure 1 presents the conceptual model for the e-enabling product requirements and their specification in an extended enterprise. It is a hub and spoke design. At the centre of the model is the hub which houses the core e-RM tool functionality. This defines the user functions in terms of protocols for inputting requirements data, searching, viewing, amending and deleting. Provision is made to allow an OEM to tailor the hub of the e-RM tool to best suit their product definition and development business processes. A vehicle can be decomposed into a number of systems, as illustrated in figure 2, and the product requirements can be decomposed and assigned to each respective system. For each of the systems, a product ontology can be developed between the OEM and the respective supplier to provide a definition of the product requirements for elicitation and documentation purposes. These ontology modules can be made pluggable into the e-RM platform to form the global and local requirements repositories. Thus, around the hub are the spokes linking to the separate pluggable ontologies for each of the different automotive systems that together form a vehicle, for example body-in-white, transmission, cockpit, interiors and electronics (figure 1). The generating of the ontologies thus can be independently created using any of the commercially available ontology development tools. This allows an OEM and their respective suppliers to both collaboratively and freely develop their own ontologies for various and separate or common automotive systems. The automotive OEM houses the global requirements management system. This system is the one single source of product requirements information for a vehicle project and is based on ontological structured global requirements repositories. The structuring and documenting of the requirements is in a common standardized electronic format. The OEM then allows their suppliers authorized access to the vehicle systems to which they are responsible for developing and manufacturing (figure 3). Thus, the suppliers have a portion of this requirements data housed in their own local clients for internal dissemination in their respective organizations.

[Insert figure 2 about here]

[Insert figure 3 about here]

To achieve conceptual heterogeneity in the specification of an automotive system the use of product ontology has been proposed as a means to realize a shared, formal and declarative representation of the product requirements. As a proof-of-concept an ontology case study has been developed. The case study is for the specification of the seating system for a vehicle. It encapsulates the product knowledge that is needed to specify the entities, functions, attributes, constraints and relations of the seating assembly. The ontology for the seating system was developed according to the guidelines proposed by Noy and McGuiness (2001). Their knowledge-engineering methodology for developing an ontology is illustrated in figure 4. The first step was to determine the domain and scope of the ontology. Then the important terms in the ontology were enumerated. This allowed the classes and the class hierarchy to be determined. For each class, the properties are defined in the form of slots. Finally, the facets of the slots were defined. The ontology editor used in this case study was Protégé-2000 developed by the SMI group of Stanford University. With Protégé, ontologies are the basis for the generation of the knowledge bases and are used to specify the knowledge representation and communication means for a domain. To elicit the information to produce the ontology a series of one-to-one semi-structured interviews were conducted with personnel within an OEM, a Tier 1 seating system supplier and two Tier 2 seating component suppliers. The personnel interviewed were from the three principal stakeholder groups within each organization: Design, Manufacturing and Purchasing. In total 28 participants were interviewed. The following functional groups were represented:

- Concepts
- Design
- Development
- Purchasing
- Cost Estimating
- Projects
- Homologation
- Production Engineering
- Materials
- Test
- Quality Assurance
- Launch
- Information Systems

[Insert figure 4 about here]

All products are designed for a purpose and they must also be fit for that purpose. Products are often designed in a top-down manner (Schachinger and Johannesson 2000) and functional modeling is a direct method for representing the functionalities for a complete product. This technique was used in the seat ontology as it provided a mechanism for the OEM and suppliers to agree, abstractly, the actual purpose and functionalities of the seating assembly that is to be designed and manufactured. Figure 5 shows part of the functional aspect of the seat ontology. One of the important functionalities is that of positioning. This encompasses positioning a potential occupant, the movement of the seat without an occupant (i.e. the pivoting to allow access to the rear seats of a three door vehicle) and the movement source (i.e. manual or powered operation). Consider for example the occupant positioning functionality, there is the need to allow a potential occupant to recline, slide and lift (raise/lower) the seat. For these functionalities the ontology has captured the key design parameters that allows the OEM and suppliers to have a shared understanding of their specification. For example figure 6 shows the specification of the slider mechanism. The principal specification parameters are the inclination angle, travel length and pitch. An ontology can be used to design the structure of the requirements repository for a vehicle system. Then for any given project, the repository can be populated with actual data and shared through out the Extended Enterprise.

[Insert figure 5 about here]

[Insert figure 6 about here]

Additionally, applying the ontology for the specification of a product allows the vehicle assembler and suppliers to work to a standard requirements vocabulary and the associated definitions for each of the individual requirements. Consider the viewpoint of a seated occupant. The occupant must be safely and comfortably supported and restrained. Figure 7 depicts some of the safety features encapsulated by the seat ontology. These features are in a vocabulary shared between the OEM and the suppliers. Their associated definitions and key parameters for specification have been agreed between the stakeholders. For example, an important safety feature is the headrest as it protects an occupant's head and neck during a rear impact to minimize the severity of injury, i.e. whiplash. The OEM has basically a choice of two design options: passive (2-way) or active (4-way). A passive headrest only has a vertical movement up and down, hence 2-way, whereas an active headrest has an additional longitudinal movement (4-way). The seat ontology states that to specify the degree of movement for a passive headrest the OEM needs to make a decision on the travel length and pitch. Whereas for an active headrest, the OEM would also need to specify the required tilt angle.

[Insert figure 7 about here]

[Insert figure 8 about here]

[Insert figure 9 about here]

The developed ontology for the seating systems is in essence a database that stores the requirements knowledge in a structured format and makes it available to the engineering designers. The ontology is accessed through a front-end developed using Visual Basic .NET. Consider the most fundamental functionalities that are available for positioning a seated occupant in a preferred posture, that is a seat can recline, slide and lift. Using the dialog box presented in figure 8, each of these functionalities can be selected for each seat in the vehicle. Additionally, there is the choice of whether the adjustment of these positioning functionalities should be manual or powered. If the lift option is required for example, the engineering designer is shown the options for lifting the seat (figure 9), i.e. lift only (just up and down – 2-way) or lift and tilt (4-way). If the manual options have been selected for moving the seat, then the designer is able to select the type of manual adjuster that should be used. From figure 10 it can be seen that the choice has been made for the seated occupant to use a handwheel adjuster to recline their seat whereas a lever type in order to slide the seat back and forth. The decision to select a particular type of adjuster is actually based on the preference of functionality for the given region of sale for the new vehicle. Europe has a preference for the handwheel whereas Japan prefers the lever type adjuster. Once an engineering designer selected the options in functionality, a series of dialog boxes are presented for entering the specification of the associated elements for each requirement. Figure 11 depicts the graphical user interface for specifying the requirements of the seat recliner and slider mechanisms.

[Insert figure 10 about here]

[Insert figure 11 about here]

7. Conclusions

Automotive Original Equipment Manufacturers (OEMs) are increasingly contracting out the design and manufacture of modular vehicle systems. In this pan national Extended Enterprise environment the concurrent engineering process requires an unambiguous and communicable definition of the product that needs to de developed. A set of complex product requirements requires the integration of information from various sources and formats. The requirements are typically aggregated into a document and represented through natural language. Often there are numerous negotiations, discussions and clarifications between the OEM and suppliers to resolve ambiguities in the interpretation of the product requirements. To reach a shared conceptual understanding of requirements the application of ontology is proposed. The ontology presented can address the problems of contextual mismatching in the use of language and associated definitions of these product requirements. A conceptual model for an ontological-based requirements management platform has been presented. This model is of a 'hub and spoke' design. This ontology can encapsulate the domain concepts for specifying the requirements of a complex product in a pan national Extended Enterprise. This functionality was illustrated through the presentation of an ontology for a sub system of a passenger vehicle developed using a standard knowledge-engineering methodology. The ontology represents the back-end of a knowledge-based tool that stores the product requirements knowledge in a structured format. User-friendly access to the domain knowledge embodied by the ontology is provided through a series of dialogs that exploit the engineer's knowledge and support the design decision processes.

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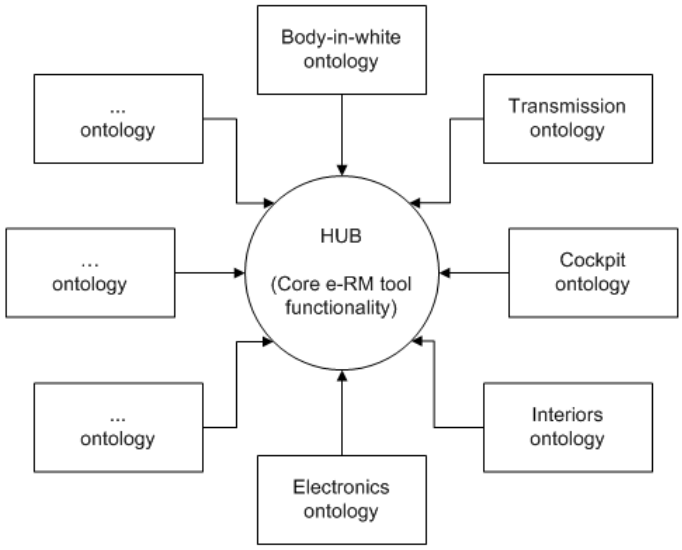

Figure 1. Hub and spoke model.

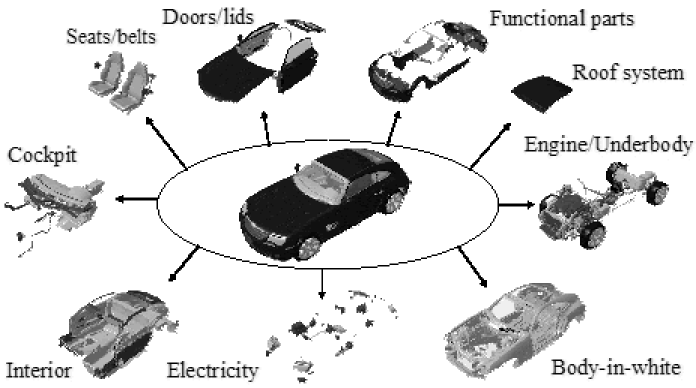

Figure 2. Vehicle systems (Marotz 2003).

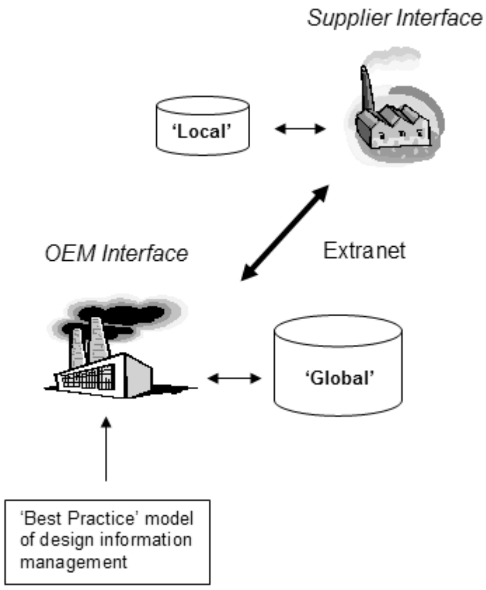

Figure 3. Global and local clients.

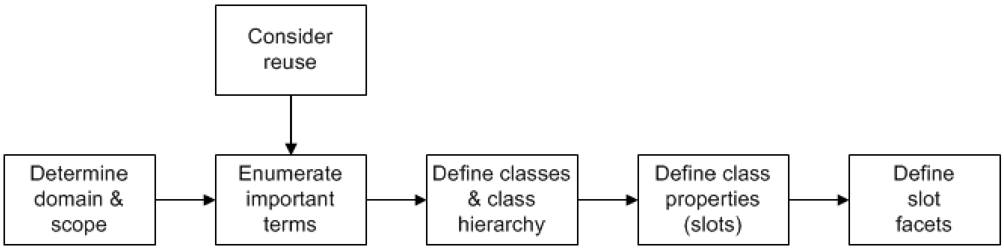

Figure 4. Ontology development methodology.

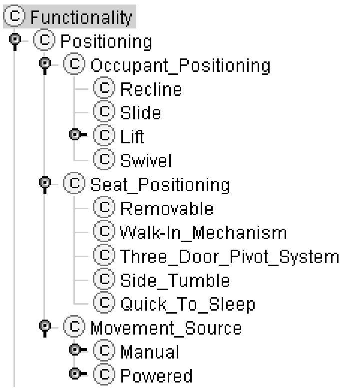

Figure 5. Seat functionality.

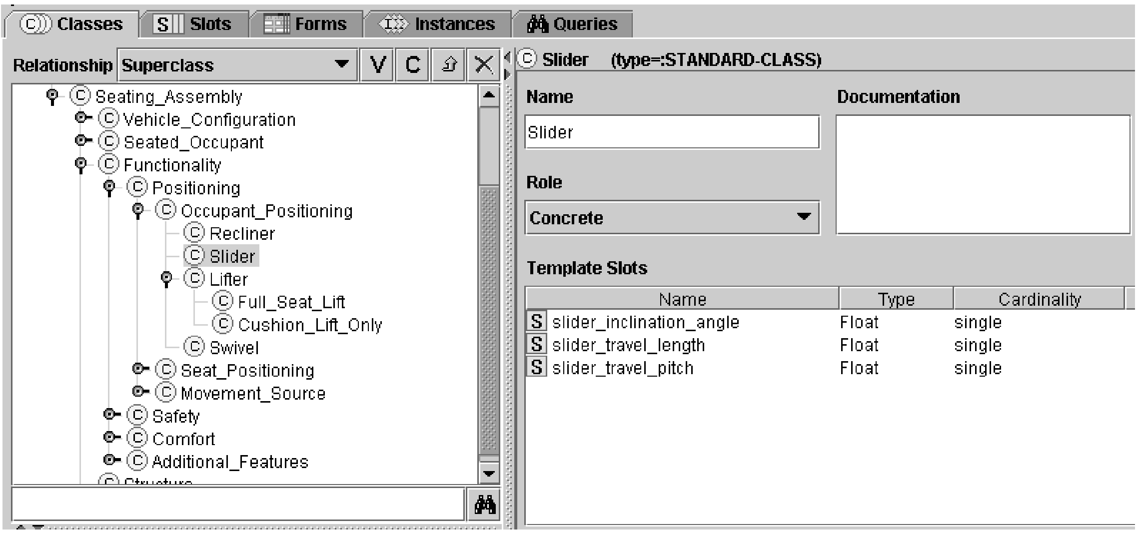

Figure 6. Slider specification elements.

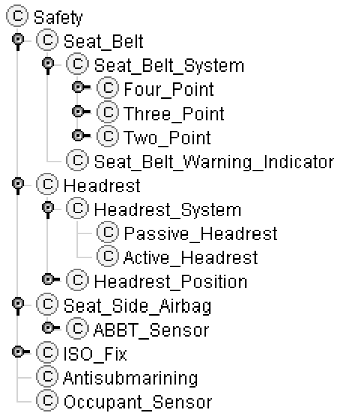

Figure 7. Safety features.

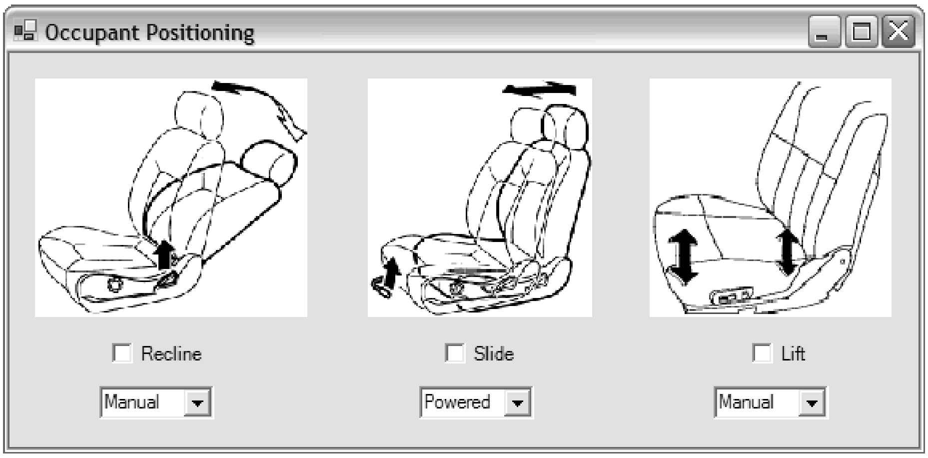

Figure 8. Occupant positioning.

Figure 9. Lifter movement.

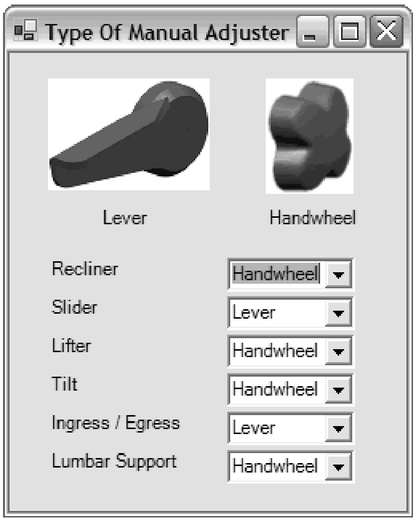

Figure 10. Type of manual adjuster.

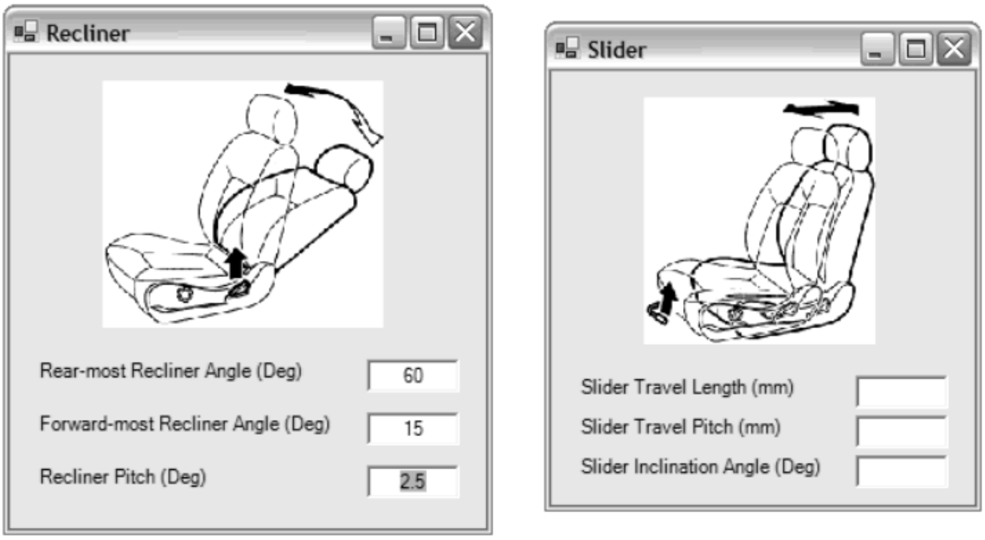

Figure 11. Recliner and slider specification.