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VIRTUAL MODEL FOR SUPPORTING COMMUNICATION OF MANUAL WORK INFORMATION THROUGHOUT SYSTEM LIFECYCLE

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1. Introduction

Today companies face the problem of sharing and reusing information in the lifecycle (LC): from design, manufacturing to operation, maintenance and recycling. The scope of this paper is to support high knowledge high value manual work (MW) in the LC. The MW is valued high because it relates to the unique, complex, and precious machinery, when the MW can be neither automated nor off-shored. MW is an important sector of the European industries. Thus, in 2008 there were 18.9 million skilled manual workers as plant and machine operators and assemblers (Eurostat, 2008). MW in Europe has to be performed more efficiently to sustain the challenges of globalization, demographic factors, and the increasing product complexity and customization.

To address the problem of handling information in the LC, there exist Product Data Management (PDM) and Product Lifecycle Management (PLM) systems (Stark, 2004; Grieves, 2006). PLM includes the worker's view and the management of the human resources and positions the people as a key element of the LC. PDM systems, while focusing on the product, also contain a large amount of MW-related information e.g. assembly, operation and maintenance instructions.

The MW information includes (1) the human actors, (2) the product in its interaction with the actors, and (3) the human and product environment throughout the LC, being in accordance with the activity theoretical model (Engeström, 1987). This information exists in the forms that are inherently difficult to articulate or formalize, for example, as human's knowledge, work practices or motivation for design solutions. This makes the MW information impossible to be gathered, stored, processed, and transmitted in the same way as the engineering product data.

Therefore, the primary goal of a system supporting MW has to capture, present, accumulate, communicate and integrate the information and knowledge on the MW throughout the LC. While being the core of such a support system, existing PDM and PLM require better integration and new additional mechanisms for accounting the MW information with the focus on improving the communication in the LC.

The results reported in this paper have been obtained in the European research project ManuVAR (211548) – Manual Work Support throughout System Lifecycle by Exploiting Virtual and augmented Reality (VR/AR) (ManuVAR, 2010; Krassi, B., D'Cruz, M., and Vink, P., 2010). The three-year-long project with the €9.7M budget involves 18 complementary organizations representing academia and industry. ManuVAR comprises five application clusters that cover the terrestrial satellite assembly, low-cost VR systems for improving the assembly lines in small and medium enterprises, AR/VR-enhanced remote online maintenance support in the railway sector, VR for training on the nondestructive techniques in the industrial plant maintenance, and VR/AR in the heavy machinery productization and maintenance.

The ManuVAR project seeks to improve MW in terms of the productivity and quality of products, adaptation to fast product changes and efficient knowledge reuse in the LC. These improvements are planned to be achieved through the systemic combination of three complementary areas: (1) ergonomics methods for MW design, evaluation, training and instructions; (2) VR/AR technology for enhancing the interfaces between the humans and the complex PLM systems; and (3) the methodology based on the virtual model (VM) concept for bi-directional (one way: technical documentation, instructions; the other way: feedback, accumulated knowledge) seamless communication through the LC among multiple heterogeneous human actors in the context of MW. The ManuVAR hypothesis is that it is this combination that makes it possible to address the whole spectrum of the MW challenges identified in industry.

The purpose of this paper is the following. First, it is to explain the added value of the VM for the communication of MW information in comparison with the conventional PDM/PLM systems; second, to discuss the architecture alternatives of the VM; and, third, to show examples of the practical VM usage.

2. Background: ManuVAR architecture and the virtual model

The architecture is based on the ManuVAR PLM model that includes several concentric layers (Krassi, B., Kiviranta, S., Liston, P., et al., 2010), Figure 1.

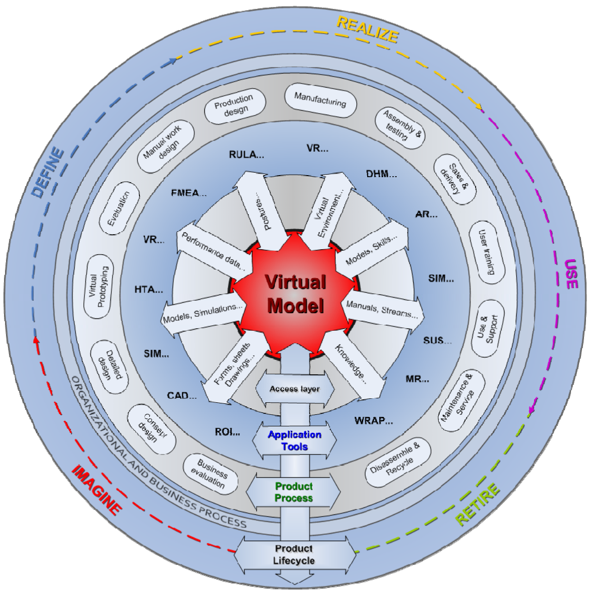

Figure 1: ManuVAR PLM model (source: ManuVAR project).

The outer layer represents the system LC, the human actors in the LC, and the organizational and business processes in the company. The next layer is the product process with respect to the MW, which is supported by the layer of the application tools (AT).

An AT is defined as one or several ergonomics methods supported by technology – VR and AR in the ManuVAR context. In ManuVAR, there are four ATs: (1) delivery of work instructions; (2) ergonomics evaluation; (3) task planning and analysis; and (4) training. Each AT implements one group of the ergonomics methods for MW support. The methods are the integral part of the AT and define its workflow, in accordance to which the AT connects the technology elements (e.g. various input, output, communication and processing hardware and software components) to implement the methods. Collectively, the ATs provide a comprehensive MW support across the LC.

The center of the PLM model is the VM. The VM (a digital mockup or a virtual prototype) is a computer-based model that substitutes a real system. It is a systemic, semantic aggregation of all information, models, processes, and simulations that describe the system in evolution throughout its LC (Krassi, 2006; Krassi et al., 2010b). The VM provides a semantic reference to various PLM repositories and to the CAD, PDM, PLM, ERP functionalities to manage information and knowledge pertaining to (1) the human actors, (2) the product, and (3) the human and product environment in the LC.

It is important that the VM does not contain the information, but it only provides the linked references to the external repositories where the information is stored. In a wider sense, the information is produced, used and stored throughout the LC. The VM links all producers and users of the information, which communicate through the VM and thus consider the VM as a single point of access to all information. Therefore, the VM becomes a shared information exchange object.

These considerations lead to the main principle of virtual modeling (Krassi, B., Kiviranta, S., Liston, P., et al., 2010): "*the VM has to be manipulated in the same way as the real object that it models. The properties of the VM are learned through interacting with it by means of virtual experiments*".

The main principle of virtual modeling has three implications in the architecture. First, the VM can be kept minimal so that its derivative properties (ergonomic evaluation, task instructions of MW etc) are obtained by virtual experiments in the VE (in analogy with generative design). This prevents the complexity explosion of the VM. Second, if an actor makes a change in the VE, the change has to be entered to the VM ("persistent reference") with the subsequent regeneration of the VE ("volatile presentation"). This helps to keep the VM and VE in synch and decoupled. Third, the actors across the LC should communicate not directly, but through the ATs and the VM. The VM as a shared object allows to synchronize multiple actors and to handle their heterogeneity.

The meaning of the ManuVAR PLM model is that it helps to structure the MW processes as a number of layers each of them offering its services to the adjacent outer layer. Thus, the VM offers the information communication bus for the ATs. The ATs support the MW processes in the product processes, which, in their turn, comprise the LC. By following the layers from the LC to the VM, one describes the process – the ManuVAR methodology – how a given customer problem can be decomposed into the product process stages in the MW context and solved by means of the ManuVAR ATs.

The ManuVAR technical architecture is obtained as a "cross-section" of the PLM model, Figure 2.

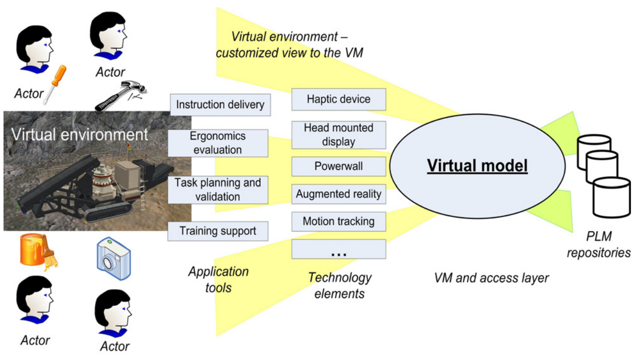

Figure 2: ManuVAR architecture (source: ManuVAR project).

The system is divided into several layers in accordance with the PLM model. The VM is in the center. It is accessed through its access layer (AL). The AT layer defines the application tool logic and orchestrates the layer of the technological elements. Finally, one or several ATs are combined by the actor (user) specific logic layer to serve the actors in a given customer problem.

3. Application example

The example illustrates how the ManuVAR system can be used by companies, Figure 3. It is based on the workflow of a vehicle development being a compiled contribution of different design departments and subcontractors. Here, ManuVAR provides a possibility for improving the ergonomics and for supporting the after-sales business in the context of maintenance. The problem formulation for this example consists of the communication between the above mentioned multi-site design teams, the regulations for taking the ergonomics into account and the utilization of virtual prototyping for shortening time to market.

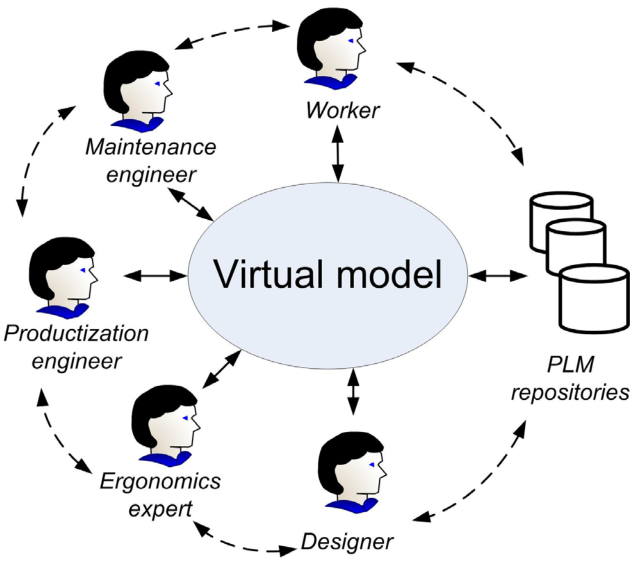

Figure 3: Application example of the ManuVAR system. Solid arrows: actual communication with the VM; dashed arrows: virtual bi-directional communication in the LC.

In the considered case, the company can introduce the ManuVAR system to streamline the communication between the multiple departments/sites and between the actors contributing to the product design from various points of views. Let us start from the situation where a new vehicle has a conceptual model available in a PDM (e.g. a 3-dimensional sketch) with the information on the problematic areas and successful design solutions in the earlier product generations. This is the initial condition for the collaborative design session to be held between design, ergonomics, productization and maintenance departments. The representatives of the first three departments could join the review meeting from their offices through a PC or from a collaboration space such as a VR cave. The maintenance representative could join the session through one's AR interface on the factory floor.

First, the ManuVAR system enables the current design status to be seen by the office/VR participants and also to be augmented over the previous product generation on the factory floor. Then, the system provides the actor context-aware interface for each department to see specifically those details of the product that are related to them and also the generic details considering all the involved participants. The actors go through a number of design possibilities and communicate via the VM in order to decide on the future development steps. The factory floor maintenance personnel are able to comment on and to interact with the same VM viewed from different perspectives by the respective ATs. The results of such a collaborative meeting will be stored to the structured knowledge repositories in the company PLM repositories through the VM as codified pieces of knowledge elements. As a result, the ManuVAR system enables the company to communicate between departments connected to different LC stages, to re-use existing information on the product, and to store and to distribute the development results automatically.

Second, the ManuVAR system architecture provides the functionality that allows the LC actors, through their interface to the product information, to utilize various ATs specific to their role in the company. In the ManuVAR project, the focus is on the MW. Hence, in this example one of the ATs could be focused on the ergonomic analysis and workplace design. As the development process for the ergonomic analysis proceeds, all data and decisions are saved in the VM so that they can be distributed via the VM to other involved actors and re-used in other processes or accessed by the actors for the knowledge reconstruction or the implementation of the agreed development steps.

Finally, the data that are formed in the ManuVAR process can be directly employed for generating the AR application of the specific task. This allows the material generated to be used for AR/VR maintenance instructions or assessing ergonomics and safety, thus producing the material for the service documentation and the end-user manuals, spare part documentation and sales brochures.

By now the vehicle has been validated and all produced material is made available in the PLM repositories accompanied by relevant metadata such as 3-dimensional model of the new vehicle and ergonomic analysis results. The ManuVAR AR system can visualize the current state to the worker on the factory floor and provide access to the specific details of each step of maintenance. The AR interface helps to submit suggestions/feedback/reports/lessons/procedures regarding the current state of the vehicle to be transferred to the PLM repositories and, hence, to be made available to support the later LC stages (e.g. assembly, maintenance, and training) and the next design generations.

4. Architectural alternatives of the virtual model

This section describes the architecture alternatives of the VM from the viewpoint of several design factors, Table 1. The following choice has been made for the first stage of the ManuVAR implementation, the tests are being prepared and their results will be published in future:

Factor	Alternatives	Analysis
Service provision model	Community model	Centrally mediated distributed model. Similar to the open-source software development, where all participants submit their results to the mediator, where those are checked, merged and made available [=linked] to all other participants using the mediation platform. Suitable for the development process. Dually-isomorphic to the market model.
	Market model	Decentralized orchestrated distributed model. Similar to the service-oriented architecture, where the service providers publish their services and those are made available [=linked] to all other participants using the broker. Suitable for the mature, readily existing services. Dually-isomorphic to the community model.
Location of data	Inside VM	Centralized aggregated data repository, for example, when a PDM is used to reference all information about the product. Such a model is easier to manage, but the VM becomes either very large and company-dependent or redundant (if the central PDM is available). The only usage of the VM is to provide an abstraction layer for the business logic built on top of the PDM.
	Outside VM	Decentralized referenced model, when several repositories are referenced from within the VM. This is similar to the meta-PDM or networked PLM systems, where the system keeps only references. Here, the VM can link a number of PLM repositories (beyond the PDM scope) in the distributed globalized business environment. It also makes the VM simpler and less application dependant. This model applies to the data connectors that have to be outside of the VM and managed by the respective PLM repositories.
Data / component models	Data-oriented model	Asymmetric database-style multi-tier architecture, where the presentation and application logic tiers use the data tier (VM, "back end"). Here, PLM repositories are considered as passive data providers, while the application logic is considered as active actors.
	Component-oriented model	Symmetric component style, where all components can be active and where, from the VM viewpoint, there is no difference between the application logic components and the PLM resources components – both have to adapt to the VM environment to access the service provision platform (either community or market). Here an advantage is that it makes it possible to modify the PLM repositories using their "back doors" without risking the system integrity.
Data communication push/pull	Push model	Component A pushes data to component B. Isomorphic to the "pull" model, but A becomes more dependent on B because A has to use B's specific interface for handling the data. Hence, such a model is good for the components pushing data to the VM, but not the other way around. Otherwise the VM will have to be aware of the types of interfaces that the components provide.
	Pull/notify model	A notifies B and B pulls data from A. Isomorphic to the "push" model, but A is dependent of B to the extent of the notification functionality. This is suitable when the VM notifies the components on the change and the components pull the updates from the VM depending on their needs.
Complexity management	Annotation model	In analogy with the semantic web technology, all pieces of information are annotated and linked. No need to generate one piece of information from another (generally this is not trivial), but it makes the model very large (collectively the information itself and links), very diverse, with many duplications and this might make configuration/version control harder to implement.
	Generative model	In analogy with the generative design and model driven architecture, the secondary/volatile information is generated from the primary/persistent/invariant information given the rules of the generation. This helps to keep the size and diversity of the model smaller and to handle the configuration/version control easier.
Change management	Synchronized model	A change in a component is fed to the VM so that two models (e.g. a VE and a CAD model) get synchronized. A problem is the duplication of the same information in both models, which makes the change management very complex when there are many tools.
	Generative model	A change in a component is fed to the VM, and then the component pulls its updated, "regenerated" model from the VM. This refers to the situation when the VM becomes a common, shared object, which can be modified by all components. All changes become immediately distributed and all components can pull/re-generate their models from the common updated VM. Such a model is suitable for change management with many components.

Table 1. Virtual Model architecture alternatives

– Community service provision model
– Data (information, knowledge elements) and connectors are located outside the VM
– Component-oriented symmetric model
– Push for component - VM communication
– Notify/pull for the VM - component communication
– Complexity management: currently – annotated model; in future – generative model
– Change management: generative model

5. Integration of the virtual model with PLM systems

We present an example of how the VM, which is designed in accordance with the architectural choices described in the previous section, can be used for the communication between two ATs supporting different aspects of MW at different LC stages and an external PLM repository. The example is based on the imaginary "sticker note" scenario when a part of a product is commented by one AT, the comment is saved in the PLM repository and distributed as a feedback to all other ATs that can make use of the comment. This scenario is easy to grasp, but it generalizes a group of functionality for the bi-directional communication in the LC. A simplified diagram is shown in Figure 4.

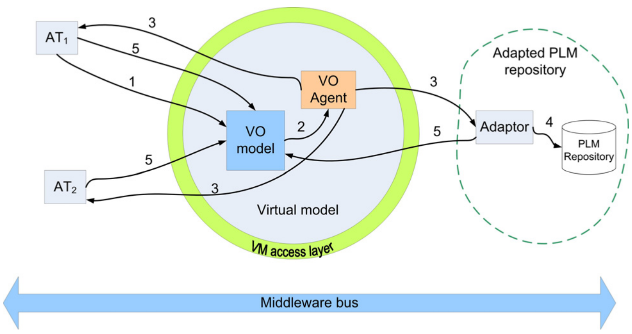

Figure 4: Example of the VM usage.

The user of AT1 leaves a comment in its virtual environment. AT1 calls the VM through its access layer (AL), (1). The AL handles the call to the Virtual Objects (VO) model. VOs are abstract data objects with a reference, name and type, for example, product parts, properties, subscribed users/ATs, services, rules. The VO model is a table of links that keeps the structure of the interconnected VOs. The depth and granularity of the VO model depends on the application, but it does not replace the structures stored in PLM repositories, e.g. if the product structure is stored in a PDM, the VO model provides a link to the structure instead of replacing or duplicating it. The VO model invokes the VO agent (2) that passes the unmarshaled content of the VOs, finds the VO subscribers (stored in the VO model), and notifies them on the VO change, (3). The subscribed ATs and PLM repositories call back the VM to pull the updated VOs (4, 5) through the VO model and VO agents. Thus, the PLM repository pulls the content of the VO for saving it (4) and the ATs pull the content of the VOs (eventually from the PLM repository) for updating their virtual environments, (5). In this way, AT2 gets updated on the content of the comment made in AT1 without a need of a direct communication between AT1 and AT2.

In practice, the AT-VM communication is a two-stage procedure. First, the AT calls the VM to provide the references of the VOs to be involved in the communication. Second, the references are provided to the technology elements of the ATs, which can use the references for the communication of the data in a variety of formats via the VM. In this way, the AT and the VM handle the references of the VOs in a data-format-independent way, while the technology elements (and their counterparts in other ATs and the corresponding PLM repositories) handle the data in the suitable formats.

The ATs handle the capture and presentation of the MW information and knowledge elements as well as ergonomics methods. The publish/subscribe/notify architecture supports a uniform dynamic bi-directional communication among an arbitrary number of ATs and PLM repositories located at different stages of the LC. It makes it easy to adapt the ManuVAR system to the existing PLM repositories by linking (not replacing) them and synchronizing all information in the VM. Also, a dynamic communication makes it possible to create modular ATs that implement atomic MW-related services instead of the conventional monolithic tools. The VM offers an application and vendor neutral abstraction layer, in which it is possible to build the functionality for knowledge accumulation by providing the VO model with a suitable semantic engine to making sense out of various data and information pertaining to the MW.

6. Conclusions and future work

ManuVAR improves MW by means of the ATs that implement the ergonomics methods supporting MW, the VR/AR technology providing a natural interface medium, and the platform enabling bi-directional communication between the ATs and various PLM repositories covering the entire LC. The VM plays an important role in all three interrelated aspects.

First, the VM-based architecture helps to make the VR/AR systems modular. A large VR/AR application can be split into smaller parts to fit concrete user needs in terms of functionality and available technology. This becomes possible not only because of the adoption of the component middleware-based architecture for the inter-component communication, but also because of the VM – the common object – that saves and distributes the information across the ATs with different MW aspects. Second, the VM approach helps to integrate the ATs with the external PLM repositories and to improve the synchronization of models through the VM. Third, the VM offers new insights to the change and complexity management in PLM.

Therefore, the VM can be considered as a complementary "middleware" layer to the commercial PDM/PLM systems. Despite the fact the commercial systems have well developed application programming interfaces (API), there is still a need for a vendor and application independent VM-based adaptation layer between the PDM/PLM systems and the ManuVAR ATs.

This paper presents the work-in-progress results of the ManuVAR project. It has analyzed the main problems related to the MW in the European industries by means of interviews, questionnaires and on-site observations in the five industry clusters. The ManuVAR ATs will be implemented as component-based applications on the described ManuVAR platform, the core of which is the VM. In future, the VM will be developed to be more structured for a better support of the storage, linkage, iterative accumulation and retrieval of various pieces of knowledge elements into searchable knowledge repositories in the entire LC. These results will be tested in the five clusters and reported in future publications. The tests are expected to confirm the validity of the chosen architectural decisions and to provide a valuable insight to the critical aspects of the system: the efficiency of the ATs, the integration of the VM with the PDM/PLM systems, and the VM-AT communication.

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