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AUTOMATION OF ROBOT OPERATION PLANNING BASED ON PRODUCT MODELLING, A CASE STUDY FOR SUSPENDED CEILING INSTALLATION ROBOTS

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ABSTRACT

This paper describes how product model information together with building knowledge is used to generate robot operation plans. This approach is explained using a case of the design and installation of a suspended ceiling system. In this case study an information reference model for suspended ceiling product models is discussed. Also suspended ceiling installation knowledge is formalized using predicate logic. Currently the developments presented in this paper are being implemented and tested using robot simulation.

1 INTRODUCTION

At the eight previous ISARC symposia many construction robot developments have been presented. Over the years more and more robots have successfully been implemented and applied at construction sites and factories. The research and development of construction robots has (obviously) been focussed at the mechanical aspects. The control of construction robots and the integration of the control with other computer systems being used in the construction industry has been of secondary importance.

Most of the control systems used for construction robots are state-of-the-art robot controllers as are being used for traditional robot applications as in the mechanical industries. These state-of-the-art robot controllers were designed from a mechanical engineering point of view and are not very convenient for creating complex robot programs. This is not an issue for most robot applications in mechanical industries because the robots are not very often re-programmed.

In the building industry most products produced are one-of-a-kind products which are produced only once or in relative small series. The problem with many applications where robots can potentially be used is that the application is often complex and as a result the creation of a robot program would be too time consuming to be worth while.

In our research project we are developing a methodology for fast and flexible construction robot programming. In previous papers [1], [2] we have presented our approach.

The foundation of our approach is the technology of standardized product modelling. Product models, containing all relevant information concerning the product described in the model, can provide very large part of the product information needed for Computer Aided Robot Operation Planning.

Currently we are working on the implementation of the concepts developed over the last years. In this implementation effort we are working on a case study. We have chosen the installation of a suspended ceiling system for our case study.

This paper presents a case study of suspended ceiling systems as they are installed in many office buildings. We have chosen this application because of it's 'assembly character' and it's level of complexity.

The objective of the case study is to investigate the feasibility of autonomous robot control based on product modelling technology. Our approach on this research is explained in [1] and [2]. This investigation consists of the formalization of construction knowledge for the installation of suspended ceilings and the specification of a product type model for suspended ceilings.

Section two describes the product 'suspended ceiling' as we are investigating in this case study. Section three describes the organization of the product models of such suspended ceilings. In section four we look at the installation process of suspended ceilings and the formalization of construction knowledge concerning this installation process. Section five describes the transformation process from product design information to process plan information. Finally in section six we present our main experiences and conclusions.

2 THE DESIGN AND THE INSTALLATION OF SUSPENDED CEILINGS

In many non-residential buildings, such as for instance offices, suspended ceiling systems are installed. In this chapter we discuss the design and the installation of such suspended ceilings. We have restricted ourselves to one particular type of suspended ceiling system. Probably the suspended ceiling systems used in other countries can be different because of difference in available products or differences in building regulations.

In paragraph 2.1 we describe the design of a suspended ceiling for an arbitrary room. In paragraph 2.2 we discuss the installation process of such a ceiling. Paragraph 2.3 discusses the robotization of the installation process.

2.1 Designing a suspended ceiling for an office room

The design of a suspended ceiling for an office room is not a very complex task. The number of alternative design approaches is limited and is strongly influenced by the ceiling system used.

In figure 1 we presented a typical design of a suspended ceiling for a rectangular room.

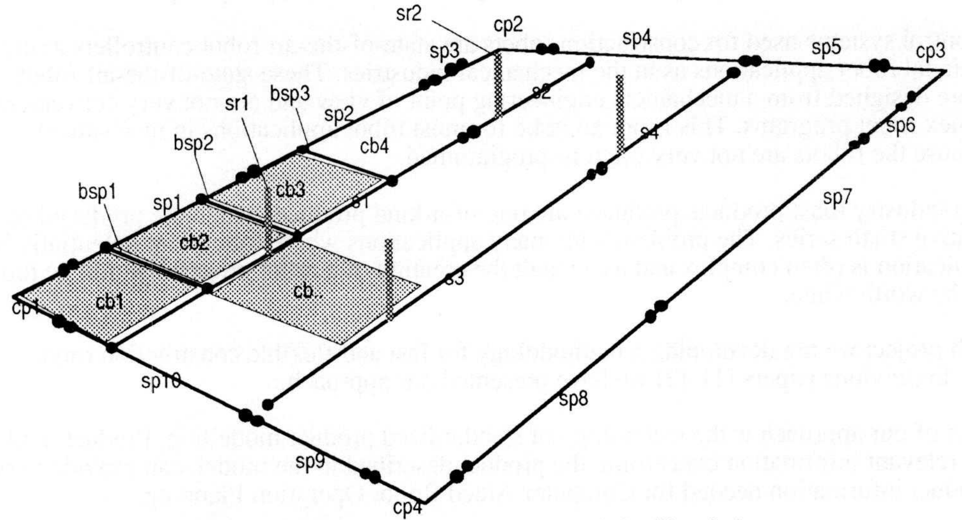

figure 1: Schematic presentation of suspended ceiling design.

At the walls of a room, a surrounding frame of the ceiling is installed. This frame consists of L-shaped metal profiles. In the corner of the spaces, special corner pieces are used. The function of the surrounding frame is to support the ceiling boards on the edges of the ceiling surface and to have nice finishing of the edges of the ceiling surface. In figure 1 the parts of the surrounding frame are indicated by codes: *cp* for corner piece and *sp* for surrounding profile.

In the length direction of the room a number (in this case 2) support profiles (indicated with code *s*) support the ceiling in the middle. These support profiles are connected to the building structure above the ceiling with suspension rods (*sr*) . Between the suspension profile (or the surrounding frame at the edges) ceiling boards are placed (*cb*'s). The ceiling boards are each separated by board separation profiles (*bps*'s).

In the design process of such a suspended ceiling there are a few alternative designs possible:

- Both the ceiling boards and the room are rectangular. The ceiling board layout design can be orientated in two directions, either lengthwise or broadwise. This often depends on the ceiling orientation in adjoining rooms.
- The ceiling layout can be 'centred' in the room by adjusting the board sizes at both sides of the ceiling instead of only at one side.

Although there are many alternative designs of suspended ceilings possible for a room, the functionality is the same.

2.2 The Installation process of a suspended ceiling

The installation of a suspended ceiling as described in the previous paragraph is not very complex. The general strategy for the installation of a suspended ceiling is:

1. mount the surrounding frame (consisting of several lengths of metal L-profile and some corner pieces) on the wall. Depending on the wall material, nails or screws are used;
2. attach the suspension rod's to the building structure above the suspended ceiling;
3. attach the suspension profile lengths (spanning the length of the ceiling) to the suspension rods and to the surrounding frame at the ends;
4. insert the ceiling boards and the board separating profiles.

There are many alternative plans possible for the installation. For instance the steps 1 and 2 can be swapped without problems.

The level of detail of the steps listed is much too low to explain a robot what to do for the installation of a suspended ceiling. For instructing a robot we have to decompose these steps into primitive robot operations. The current generation of robot controllers works with operations related to robot movements. This level is of a too low abstraction level for the describing a robot job. In [1] we explained our strategy where robot tasks are described in terms of product related primitive *required operations* such as 'place part' or 'create hole'. These required operations can be fulfilled by robot specific *proposed operations* which again decompose in robot arm movements.

2.3 Robotizing the installation process

The traditional installation process of suspended ceilings is adapted to human handling and installation. When robots are used for the same work, it often turns out that both the product and the installation process are not suitable for robot handling.

We believe that many parts of suspended ceilings need to be redesigned in order to be suitable for robotized installation. As in mechanical industry where the term 'Design for Assembly' is used, robotization in the building industry requires 'Design for Robotization'. When we look at the details of the suspended ceiling parts we can recognize many problems for robotic installation. Connection methods such a bolts and nuts are generally unsuitable for robotic installation. Many of the connections are not designed for robots. We are convinced that the majority of the assembly methods used in suspended ceiling designs can be replaced by versions which are suitable for robotic installation. Obviously the price of the product will increase, however this will be compensated by the reduced cost of efficient robotic installation. We do not deal with this issue of robotization in our research. Independently of the robot developments and design for robotic construction we investigate Computer Aided (or Automated) Robot Operation Planning. The first item for investigation is operation sequence planning.

When we look at the sequence planning of operations we can recognize three criteria influencing the sequence of operations. These are:

1. the tools to be used
2. the materials to be handled
3. the location of the operation

In a manual installation the priorities between these criteria are mostly 1,2,3 or 2,1,3 depending on the size or weight of the material or tool to be handled.

The use of construction robots opens new alternative planning approaches. For instance a planning for a construction robot could be to sort all operations on their location. In contrast to humans, robots can not move around as quickly and easily as humans can. Therefore it could probably be more efficient for a construction robot to change tools more often than to change position. However what strategy is most efficient can only be determined by the construction robot which is aware of it's own capacities. Therefore robot operations plans should never consist of a fixed sequence of operations. This approach eliminates all possibilities of alternative operation sequences in case of unexpected events. In chapter 4 and 5 we discuss how such operation plans can be generated and evaluated.

3 A SUSPENDED CEILING PRODUCT TYPE MODEL

The objective of product modelling is to integrate product information relevant for all applications involved with the product. In current research most attention is paid to the organization of product models for design related information. In our research we investigate the extension of the product model applications to production planning and more specific operation sequence planning.

In this chapter we present the structure of a suspended ceiling (product) model. The information organization of product models for a specific category of products is described in a so called *product type model* (PtM). A product type model is a meta model describing the structure of product models for a category of products, in our case suspended ceilings. We have limited ourselves to a special kind of suspended ceilings. We do not have the intention to develop a complete product type model for all types of suspended ceilings. This PtM in this paper is developed only for the investigations in our research project however this does not limit the usability of this PtM to robot operation planning.

In figure 2 the main structure of the PtM is presented. The PtM for suspended ceilings defined in terms of entities defined in the General AEC Reference Model (GARM) , developed by Gielingh [3]. The most important principle of the GARM used in the PtM is the so called *Technical Solution – Functional Unit decomposition*. In the TS-FU decomposition there are two views on objects: a functional view and a technical view. The functional view is modelled in Functional Units and the technical View in Technical Solutions. A Technical Solution fulfils the (required) functionality specified in a Functional Unit. Technical Solutions can either be third party products or they can decompose into lower-order Functional Units.

Figure 2 shows the decomposition structure of the suspended ceiling model. The TS 'Suspended Ceiling System Design' decomposes into three lower order Functional Units: 'wall connection', 'suspension construction' and 'element layout'. Each of these Functional Units is fulfilled by a Technical solution which again decomposes into lower-order Functional Units. Besides the collection of functional units in which a technical solution decomposes, the relations between the component functional units are also significant. A brick wall is not equal to a pile of bricks witch cement. In figure 2 we have included the relations 'is connected-to' and 'supports'. Depending on the product model application, different relations are of significance. Also geometric representations of the Functional Units and Technical Solutions incorporate relational information about adjacency, but these relations are implicit and can not always be recognized easily without aid of geometric reasoning tools.

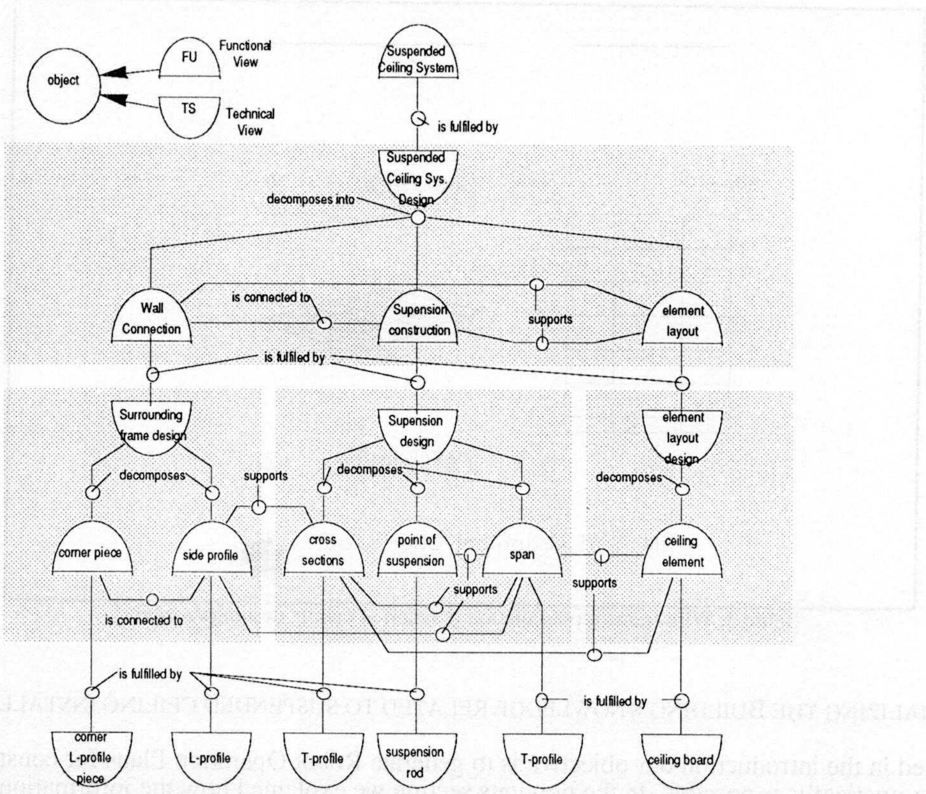

figure 2: The main structure of the Suspended Ceiling Product type Model

In figure 2 we modelled the relations 'supports-is supported by' and 'is connected to' between functional units belonging to the decomposition of a Technical Solution. Relations also exist between Functional Units belonging to different TS decompositions. These relations are specializations of the relations between functional units higher up the decomposition tree. For example the relation 'supports' between the entity 'side profile' and 'cross section' is a specialization of the 'is connected to' relation between 'wall connection' and 'suspension construction'.

3.2 Creating a suspended ceiling product model

The design of suspended ceilings is not directed by creativity but mainly by the type of ceiling system used. In most spaces where suspended ceilings are used, the design of the suspended ceiling is a standard procedure. Therefore the Technical Solution 'Suspended Ceiling Design' can also be described in terms of a procedure. We have implemented such a procedure for the prototype product modeller ProMod [4]. A special procedure is evaluated for every occurrence of the Technical Solution 'Suspended Ceiling Design'. The evaluation of the procedure results in the generation of a complete decomposition tree of the technical solution according to the values of the procedure parameters such a length, width, height. These parameter values determine the number of profiles and ceiling boards used in the ceiling design.

The ceiling design procedure is programmed in the ProMod modelling language XPCL [5]. Figure 3 shows a wire frame representation of a design generated using this procedure.

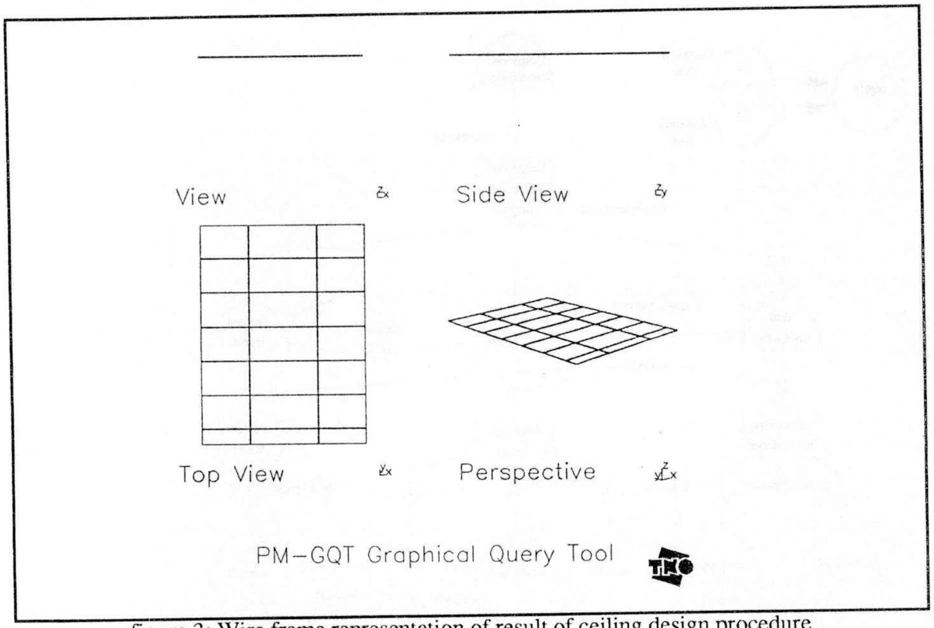

figure 3: Wire frame representation of result of ceiling design procedure

4 FORMALIZING THE BUILDING KNOWLEDGE RELATED TO SUSPENDED CEILING INSTALLATION

As mentioned in the introduction our objective is to generate Robot Operation Plans for construction robots as automatically as possible. In the previous section we explained how the information in a product model for suspended ceilings is organized. We believe that well structured design information such as stored in a product model can be used to generate robot operation planning. The translation of design information into process planning information is a translation process in which construction knowledge is applied to the design information. The use of a high semantic product model such as presented in the previous section enables the (re-)use of the design information for other applications such cost calculation and process sequence planning. In this chapter we will discuss the representation of construction knowledge and the transformation of design information into a process plan.

4.1 Representing suspended ceiling installation knowledge using Predicate Logic

Unfortunately natural languages are unsuitable for the representation of knowledge in computer applications. In the world of artificial intelligence this fact has been recognized long ago and alternative representation of real world knowledge have been found. One method of representation of knowledge often used is predicate logic. Rich [6] explains this principle in her book. In this paragraph we use predicate logic to represent suspended ceiling installation knowledge.

The use of predicate logic is probably best explained with a simple example: assume the following statement: every part of the suspended ceiling system has a corresponding operation which installs or realizes the part. In predicate logic this is notated as the following *statement*:

- $\forall x \; \exists I_x \; \mathtt{IsCeilingPart}(x) \land \mathtt{IsOperation}(I_x) \land \mathtt{Installs}(I_x, x)$

Using this notation we can formulate many rules concerning the installation of the suspended ceiling. Because of the mathematical formulation of these real world *facts*, we can interpret these *statements* representing real world facts using computer programs and apply these to the contents of product models.

Also more complex reasonings can be formulated in predicate logic. For instance:

- Every CeilingBoard which is supported by a profile of the support structure can only be installed after the supporting profile is installed.

$$\begin{array}{l}
\forall x\ \exists y\ \exists I_x\ \exists I_y \\
\mathtt{IsCeilingBoard}(x)\ \wedge \mathtt{IsSupportProfile}(y)\ \wedge \\
\mathtt{IsOperation}(I_x)\ \wedge\ \mathtt{IsOperation}(I_y)\ \wedge \\
\mathtt{Installs}(I_x, x)\ \wedge\ \mathtt{Installs}(I_y, y)\ \wedge \\
\mathtt{Supports}(y, x) \\
\rightarrow \mathtt{Precedes}(I_y, I_x)
\end{array}$$

We need to evaluate all predicate facts used in the construction knowledge predicates from the product model. This is possible when all names of entities and relations in product models are standardized by a product type model. In the statements used in the examples of this paragraph we used terms such as: 'IsSupportProfile(x)' This fact can only be evaluated automatically when the Class with name 'SupportProfile' exists in the PtM.

A less readable but better computer interpretable form for statements would be:

$$\begin{array}{l}
\forall x\ \exists y\ \exists I_x\ \exists I_y \\
\mathtt{IsElementOf}(\mathtt{CeilingBoard}, x)\ \wedge \mathtt{IsElementOf}(\mathtt{SupportProfile}(y)\ \wedge \\
\mathtt{IsElementOf}(\mathtt{Operation}(I_x)\ \wedge\ \mathtt{IsElementOf}(\mathtt{Operation}(I_y)\ \wedge \\
\mathtt{HasRelation}(I_x, \mathtt{Installs}, x)\ \wedge\ \mathtt{HasRelation}(I_y, \mathtt{Installs}, y)\ \wedge \\
\mathtt{HasRelation}(y, \mathtt{Supports}, x) \\
\rightarrow \mathtt{HasRelation}(\mathtt{Precedes}, I_y, I_x)
\end{array}$$

In this form only two predicates are used: 'IsElementOf' and 'HasRelation'. The arguments of these predicates correspond to entities and relations in the product model.

4.2 Classification of building knowledge

All facts used to generate robot operation plans from design information can be divided into a number of categories according to the scope of the facts in the statement. When the facts of the statements refer to Ceiling Product Model specific entities or relations that the statement is clearly *product type specific*. An example of a product type specific statement is :

- Profiles of the surrounding frame of standard length are installed before custom length profiles are installed.

$$\begin{array}{l}
\forall x\ \exists y\ \exists I_x\ \exists I_y \\
\mathtt{IsSurroundProfile}(x)\ \wedge \mathtt{IsSurroundProfile}(y)\ \wedge \\
\mathtt{IsOperation}(I_x)\ \wedge\ \mathtt{IsOperation}(I_y)\ \wedge \\
\mathtt{Installs}(I_x, x)\ \wedge\ \mathtt{Installs}(I_y, y)\ \wedge \\
\mathtt{Adjacent}(x, y)\ \wedge\ \mathtt{StandardSize}(x)\ \wedge\ \neg \mathtt{StandardSize}(y) \\
\rightarrow \mathtt{Precedes}(I_x, I_y)
\end{array}$$

Other statements such as:

$$\begin{array}{l}
\forall x\ \exists y\ \exists I_x\ \exists I_y \\
\mathtt{IsFunctionalUnit}(x)\ \wedge \mathtt{IsFunctionalUnit}(y)\ \wedge \\
\mathtt{IsOperation}(I_x)\ \wedge\ \mathtt{IsOperation}(I_y)\ \wedge \\
\mathtt{Installs}(I_x, x)\ \wedge\ \mathtt{Installs}(I_y, y)\ \wedge \\
\mathtt{Supports}(y, x) \\
\rightarrow \mathtt{Precedes}(I_y, I_x)
\end{array}$$

Refer to general knowledge applicable to every (building) project. This kind of building knowledge could perhaps best be standardized at a national or international level.

According to the scope of the statements we classify the statements in the following categories:

- *General Building Knowledge*:
  knowledge applicable to every building product and project. This kind of building knowledge is to be standardized.
- *Product Type Specific building knowledge*:
  knowledge applicable to specific product types such as suspended ceilings. This kind of building knowledge should be co-ordinated by the branch organizations such as suspended ceiling installers.
- *Product Specific Building Knowledge*:
  knowledge applicable to specific products of a certain supplier, e.g. the suspended ceiling system of supplier Jones. This building knowledge should accompany every suspended ceiling purchased from a supplier. The product supplier is responsible for this building knowledge.
- *Project Specific Building Knowledge*:
  knowledge applicable to a specific building project. This building knowledge is supplied by the (sub) contractor.

Together with the specialization of the knowledge the scope an life-time of the knowledge diminishes. Project Specific are only relevant for one or perhaps two building projects while General building knowledge will perhaps be standardized at an international level and be used of thousands of building projects.

More specific knowledge must overrule more general knowledge. Otherwise exceptional projects or product could never be dealt with.

5 FROM PRODUCT MODEL TO ROBOT OPERATION PLANS

In the previous chapter we described how building knowledge can be formulated using predicate logic. In this chapter we describe what the result is of applying building knowledge to product design information.

5.1 Robot operation plans

When we apply the ceiling installation statement to a filled product model we can generate a sequence planning for the installation of a suspended ceiling. In this paragraph we show how we generate a planning for the installation of the surrounding frame of the ceiling. We use the ceiling design as presented in section two.

We apply two statements concerning the surrounding frame to the design of section two. The statements are:

1
$$\begin{array}{l}
\forall x\ \exists y\ \exists I_x\ \exists I_y \\
\mathrm{IsSurroundProfile}(x)\ \wedge \mathrm{IsSurroundProfile}(y)\ \wedge \\
\mathrm{IsOperation}(I_x)\ \wedge\ \mathrm{IsOperation}(I_y)\ \wedge \\
\mathrm{Installs}(I_x, x)\ \wedge\ \mathrm{Installs}(I_y, y)\ \wedge \\
\mathrm{Adjacent}(x, y)\ \wedge\ \mathrm{StandardSize}(x)\ \wedge\ \neg\mathrm{StandardSize}(y) \\
\rightarrow \mathrm{Precedes}(I_x, I_y)
\end{array}$$

2
$$\begin{array}{l}
\forall x\ \exists y\ \exists I_x\ \exists I_y \\
\mathrm{IsSurroundProfile}(x)\ \wedge \mathrm{IsCornerPiece}(y)\ \wedge \\
\mathrm{IsOperation}(I_x)\ \wedge\ \mathrm{IsOperation}(I_y)\ \wedge \\
\mathrm{Installs}(I_x, x)\ \wedge\ \mathrm{Installs}(I_y, y)\ \wedge \\
\mathrm{Adjacent}(x, y) \\
\rightarrow \mathrm{Precedes}(I_y, I_x)
\end{array}$$

Figure 4 shows the structure of the resulting operation plan. The arrows indicate the relation ‘requires the installation of’.

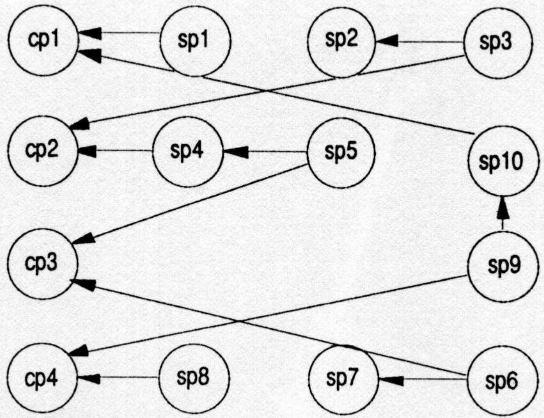

figure 4: Robot Operation Graph for installation of surround profile

The operation sequences showed in figure 4 form a graph of operations and precedence links. Clearly there are still many alternative routes possible to carry out all operation sequentially. That is why we call such a graph a neutral robot operation plan. According to the capabilities of the construction robot used, some of the operations can be carried out simultaneously.

The robot operation plan presented in plan contains only the necessary precedence relations between all required activities. We believe that this is the most suitable representation for the transfer of robot operation planning information. According to the circumstances of a construction robot in a specific situation, the flexibility in the robot operation plan allows more intelligent behaviour of the robot because the robot can easily react to special situations and alter the original planning sequence. This is made possible because the planning graph also contain information about alternative planning sequences.

There are however a number of conditions to which an operations plan must satisfy: clearly the most important condition is that the graphs may not be cyclic.

5.2 Evaluation of Robot Operation Plans using simulation

Using the robot simulation system Robcad we investigate the evaluation of the generated robot operation plans and test the translation of operations into robot movements.. Figure 5 shows a shot from a simulation where a surround L-profile is installed. The robot used in this simulation is a functional prototype which has the right functionality to install suspended ceiling parts. From mechanical engineering point of view, the design of this robot is probably not very realistic.

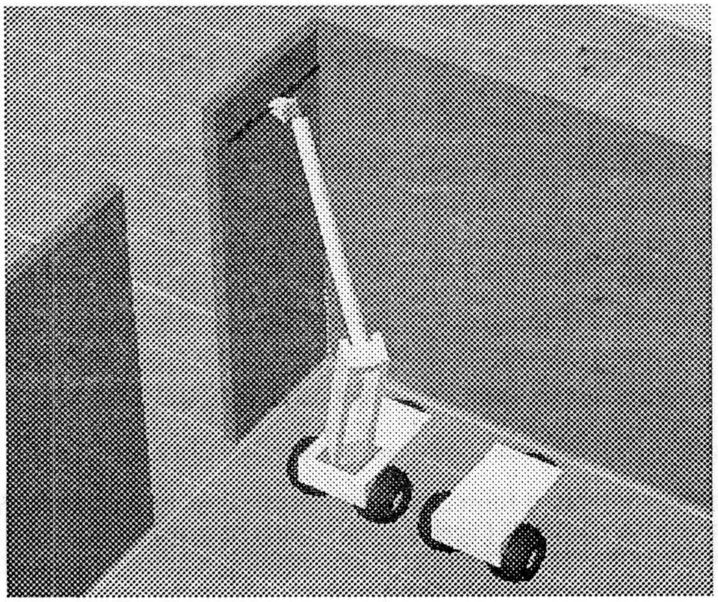

figure 5: Robcad visualization of ceiling installation robot

6 SUMMARY AND CONCLUSIONS

The combination of product models based on standardized Product type Models and predicate logic for building knowledge representation, seems a very powerful combination for generating template robot operations plans. These plans are a collection of operation graphs. These graphs can be interpreted by robot control systems and a plan of attack can be generated.

7 ACKNOWLEDGEMENTS

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