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REQUIREMENTS MANAGEMENT IN EARLY STAGES OF MECHATRONIC DESIGN BY VISUALISATION OF INTERDEPENDENCIES

C. Stechert, S. Bauer, H.-J. Franke and H. Meerkamm

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1. Introduction

The development of mechatronic products is characterised by multi-disciplinary relations. Carefully modelling relations throughout the development process allows identifying goal conflicts, optimisation and innovation areas and effective change management [Stechert, Alexandrescu, Franke 2007]. A quantitative relation modelling is an important and helpful approach. But sometimes it is too complex to discuss it with customers or it requires too much work in early stages of a design process where it is not clear whether the inquiry will lead to an order or not. In many cases, it is even not possible to unterstand the total system of relations in a holistic way.
A solution to handle interdependent requirements of mechantronic products can be found in a new approach developed within the German Research Foundation (DFG) individual grants programme "DFX-oriented support of multicriterial decision making tasks in product development". There, a concept for a method to visualize design tasks based on the dependencies between requirements allowing a lot of helpful applications has been developed and implemented prototypic. Beside a short introduction later on in this paper, the concept of that method is explained in [Bauer, Meerkamm 2007].
A good example for demonstration of the benefit of the visualisation method handling interdependent requirements of mechatronic products can be found within the Collaborative Research Centre 562 "Robotic Systems for Handling and Assembly – High Dynamic Parallel Structures with Adaptronic Components". There, concepts for design and modelling of parallel robots for high operating speeds, accelerations and accuracy are developed. As a mechatronic product several disciplines are necessary to set the robot in operation. This results in relatively complex products with complex relations. Approaches are developed to handle these relations effectively on different levels. In this paper it is explained how those relations can be modelled, visualised and handled with the new visualisation tool.

2. Visualisation of interdependent requirements

In detail, the visualisation method is explained in [Bauer, Meerkamm 2007]. According to the approach explained there, the desired product properties (requirements) are to be compared pairwise in a matrix with regard to their dependency at first. After [Weber, Werner 2000], *product properties* describe the product's behavior and cannot be directly determined by the designer. To compare the properties, a measuring number between -5 and 5 is assigned. Thereby stands -5 for maximum competition while highly complementary properties are characterized by the assignment of the measuring number +5. Here, it is important to understand, that the quantification of dependencies between a pair of product properties is based upon the significant product characteristics (*characterisics* define the product and can be directly determined by the designer [Weber, Werner

2000]) in each case. Consequently by editing the matrix of interactions, information about product characteristics is implicitly brought in. As it is shown later, those characteristics will also be found in the graphic representation. However, since the comparision of properties is always made based on the underlying product characteristics, the visualisation method can only be applied for products with known relations between properties and characteristics, e.g. for existing or similar to existing systems.

On basis of the matrix of interactions, a graphic representation of the considered interacting properties is built in the next step. For this purpose, each property is represented by one point in a space (property point). The positions of these property points are calculated so that the representatives of complementary (competing) properties show a short (great) distance between each other.

The calculation of those distances is done by using an analogy from mechanics. For this purpose each interdependency between two properties is modelled as a force between the representing property points. A force between two property points P_i and P_j is thereby defined as a function of the accordant distance in the property space d_{ij} and the interdependency factor w_{ij} determined in the interaction matrix.

By calculate those distances d_{mn} for all property pairings, for which the resulting forces at each property point equal zero and consequently the overall system is in equilibrium, the desired visualization is obtained (Figure 1).

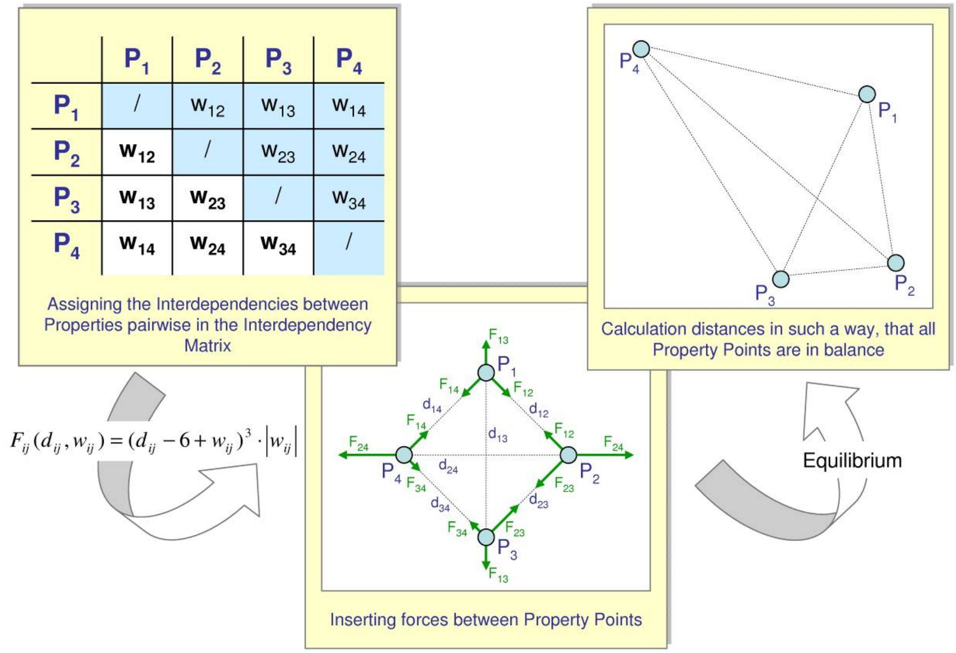


Figure 1. Approach by the forces model [Bauer, Meerkamm 2007]

This balanced structure can be visualised in up to three dimensions. In figure 2 a visualization of interacting properties (with two dimensions) is mapped and the significance of clusters and dimensions in general is explained.

In the dimensions (arbitrary number of interrelated dimensions, based on two or three independent basic dimensions) of the visualization space, all those characteristics are found again that provided the basis in the estimation of the dependencies documented in the interdependency matrix. Clusters of property points indicate hierarchically higher-positioned goals.

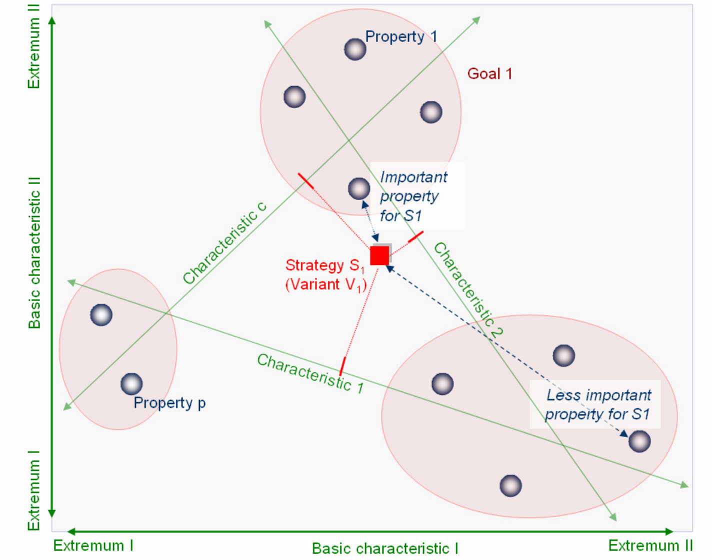


Figure 2. Interpretation of a visualization result (here: two dimensions)

Thus, this visualization is a strongly simplified representation of a real multidimensional design space. However, the simplifing reduction to maximum three dimensions is necessary, since a person is normally only able to think in up to three dimensions.
Knowing that the visualization space is a simplified design space, it becomes clear that each arbitrary point V_j in the visualization space basically represents a variant of the considered technical system. Thereby applies: A great (short) distance of point V_j to another arbitrary property point P_i means that in the considered variant V_j the property P_i inheres a low (high) importance or weighting respectively.
Thus a technical system is simultaneously represented in two ways in this approach: On the one hand it is defined by the determination of its fundamental characteristics. Hereby, the pertinent setting of characteristics is obtained by plumbing from the selected point V to the accordant characteristic axis. On the other hand, the technical system is represented by the definition of its properties and indication of the respective degrees of compliance.
On basis of such visualization it is now possible to carry out the determination of weightings for the properties simply by selecting a point (strategy point S) (see Figure 2). The distance of a property point from the strategy point is thereby the measure for the significance attributed to that respective property.
By an appropriate choice of properties, the visualization can also be used as a basis for the setting up of a product program. This succeeds then when the different areas can be attributed to certain market segments in the visualization. All these applications of the visualisation can be shown using the method (respectively the corresponding software tool) for the product group parallel robots.

3. Parallel robots

Parallel robots are characterised by closed kinematic chains with drives placed in or near the rack. This leads to relatively small moved masses and therefore high dynamics. The closed loop of structural components leads to high stiffness. Parallel robots can be made up in a wide variety of possible structures depending on desired degree of freedom (dof) and workspace characteristics. For instance, following Grüblers formula a robot with dof = 3 in space can be realised with two or three chains connected through a working platform. For three chains it is possible to use three similar chains with dof = 5 each, but it is also possible to use three different chains with dof = 4, 5 and 6. But even if two chains provide the same dof they can be made up in a different way, e.g. RUS (rotational, universal, spherical joint), UPS (universal, prismatic, spherical joint) or PUS (prismatic, universal, spherical joint). Chapter 3.1 shows an example for one possible structure: The dof = 6 HEXA robot of the SFB 562.

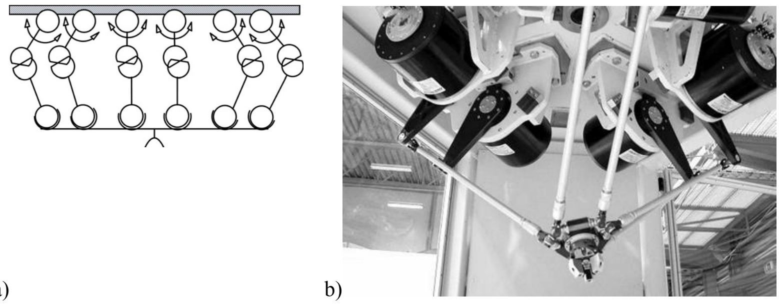
The disadvantages compared to serial robots are mainly a small ratio of workspace to installation area and the existence of singularities within the workspace. To overcome these drawbacks new design, analysis and control methods as well as new and optimized structure components (e.g. adaptive joints [Stechert, Pavlovic, Franke 2007] and rods [Rose, Keimer, Breitbach, Campanile 2004]) were developed.

As shown e.g. in [Stechert, Alexandrescu, Franke 2007] the development of a parallel robot concerns a wide range of different knowledge domains and different partial models (requirements structure, functions structure, product structure, CAD models, kinematic and dynamic models, control, robot programming, cost structure). In early phases it is hardly possible to describe the complex relations, because physical and mathematical equations need certain input data. For instance, the appearance of singularities within the workspace cannot be discovered before the characteristics of the kinematic chains (e.g. rod length, joint angles) were defined.

3.1 The Hexa structure

A HEXA structure (6-RUS) consists of six kinematic chains to provide a dof of 6. In principle, the chains consist of a rotational drive (dof = 1), a universal joint (dof = 2) and a spherical joint (dof = 3). Figure 1a) shows the described kinematic principle. Figure 1b) shows the real robot as it was developed within the SFB 562, cp. [Hesselbach, Budde, Bier, Pietsch, Otremba, Plitea 2004].

This robot has to fulfil the goal of high dynamic. On the picture the big powerful drives are visible that allow high accelerations and speed at the tool centre point (TCP). Another specialty about this robot is the embodiment of the spherical joints at the working platforms: It is realised by a serial connexion of a rotational and universal joint. This allows larger joint angles and re-use of the universal joints [Hesselbach, Budde, Bier, Pietsch, Otremba, Plitea 2004]. On the other hand this composition leads to additional joint related singularities. This has to be considered during simulation and control.



a) b)

Figure 3. HEXA robot of the SFB 562: a) kinematic principle, b) photograph

3.2 Requirements analysis

At present few parallel robots are sold as mass products but customized to the needs of a special customer. Re-use of knowledge, thence configuration through a modular concept and effective change management through a systematic holistic view is helpful to provide the desired fast time-to-market as well as high quality and optimal products to the customer needs. But many customers want some kind of Swiss army knife, when asked for their needs. So as a first step manufacturer and customer have to discuss the customer wishes according to what is realisable to find a strategy for the new product (general view). In later phases a first qualitative structuring of requirements regarding single components help identifying conflicts and can lead to new research fields and innovation.

3.2.1 General view

The general view onto the robot has to consider at least the robots surroundings at the installation area and the product that has to be assembled. The two left columns of table 1 show nine typically desired properties of a parallel robot. One customer wish is a high payload (P1) to be able to assemble heavy parts. A large workspace height (P2) as well as large workspace diameter (P3) gives the possibility to handle big parts or to place tool holders into the workspace, so that the robot can change its tools according to the assembly step. A good and easy accessibility (P4) is desirable on the one hand to allow an easy implementation into an existing automation chain and on the other hand to allow ergonomic charging and maintenance. High speed at the TCP (P5) is useful especially for pick-and-place tasks with long trajectories to shorten the cycle time. A high acceleration (P6) allows for shorter cycle times even for assemblies without long trajectories. The high accuracy (P7) is necessary especially for assembly (e.g. cell phone casings and boards). The last two properties consider difficult to estimate economic impacts. Low energy consumption (P8) is often the key factor for efficient work, because it drastically exceeds the purchase price. Nevertheless low manufacturing costs (P9) as a basis for pricing is an important basis for the customer's buying decision.

The right side of table 1 shows the correlation matrix, i.e. the result of an expert rating of pairwise correlations between properties. Just to give some examples, in cell P3P4 a big supporting relation (5) is marked. That describes the fact that the larger the workspace diameter the better will be the accessibility (as long as no additional vertical frame is necessary, e.g. for rack stiffness reasons). The cell P6P9 shows a big goal conflict. Here it is assumed that for a high acceleration at the TCP a powerful direct drive is necessary. Drives are bought-in parts of the robot. So the purchase price of the drives is directly added to the manufacturing costs. Firstly, direct drives are more expensive than normal drives with attached gears units. Secondly, the more power a drive provides normally the higher is the purchase price. The drives of a high dynamic Hexa robot can be seen as one of the main cost drivers.

Table 1. Qualitative correlation between general properties

	Properties	P1	P2	P3	P4	P5	P6	P7	P8	P9
P1	High payload		0	-3	-1	-5	-5	-1	-5	-5
P2	Large workspace height			5	5	2	-2	-2	-5	-4
P3	Large workspace diameter				5	2	-2	-2	-5	-4
P4	Good/easy accessibility					-1	-1	0	0	-1
P5	High speed at TCP						5	-5	-5	-5
P6	High acceleration at TCP							-5	-5	-5
P7	High accuracy at TCP								0	-3
P8	Low energy consumption									3
P9	Low manufacturing costs									

3.2.2 Detailed view

As described in chapter 3.1 joints play an important role for the overall performance of a parallel robot. Five main properties are shown in Table 2. Low weight (P1) is essential for a moved robot component to reach a high payload or a high dynamic. High stiffness (P2) of the joint is demanded to provide high stiffness of the whole robot and therefore allow a good accuracy. To enlarge the usable workspace and to decrease areas of joint related singularities robot joints should provide large angular movements (P3). For fast movements of the kinematic structure and a high efficiency factor a low friction (P4) (e.g. in the bearings) is demanded. For precise movements during assembly tasks joints should have a low clearance between the moving surfaces.

The correlation matrix in table 2 again shows how the joint experts would relate the properties to each other having conventional solutions in mind. For instance, conventional joints used to realise a compromise for the goal conflict (-5) between friction and clearance (P4P5) by using e.g. prestressed needle roller bearings.

Table 2. Qualitative correlation between joint related properties

	Properties	P1	P2	P3	P4	P5
P1	Low weight		-5	2	0	0
P2	High stiffness			-3	-2	5
P3	Large angular movement				0	0
P4	Low friction					-5
P5	Low clearance					

3.3 Visualization and Discussion

From the correlation matrices displayed in table 1 and table 2 the property spaces were generated and are shown in figure 4 and figure 5.

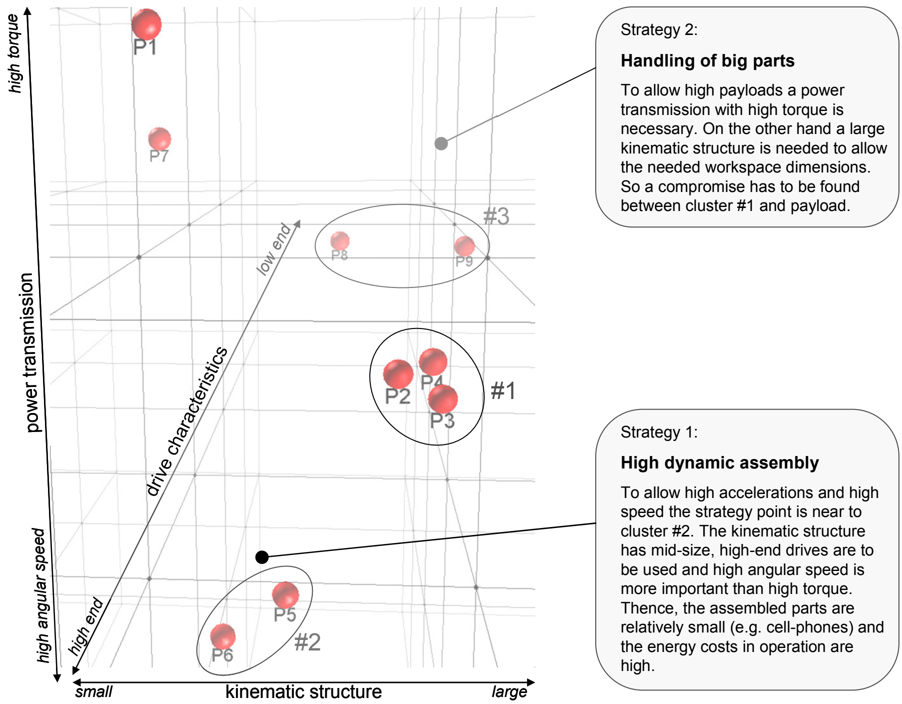


Figure 4. Visualisation of general properties and possible product strategies

Figure 4 shows the general properties of a parallel robot system. It can be observed that some properties are put into clusters. One cluster consists of the workspace related properties workspace height, dimension and accessibility. A second and third cluster are related to dynamic (acceleration, speed) and costs (energy consumption, manufacturing costs). An axis *drive characteristics* can be drawn between the last mentioned clusters. The scaling starts with powerful but expensive drives at cluster #2 and ends with cheap but less powerful drives at cluster #3. This axis shows something new: High accuracy is placed at the side of the expensive drives. That is true, when considering that tolerances and precision is better for expensive drives. Regarding the triangular relation between cluster #3, #2 and payload shows that the latter two both need powerful drives, but cannot be fulfilled at the same time. With some simplification the following equation (1) shows the effect behind it:

$$P_{drive} = T_{drive} \cdot \omega_{drive} \quad (1)$$

To move the payload via the kinematic structure the drives have to apply a torque T_{drive}. The angular speed ω_{drive} leads to the speed at the TCP subject to the transmission ratio of the kinematic structure. Thus, for the same provided power a compromise between torque and angular speed has to be found. Lastly, a third axis can be drawn describing the effect that a larger kinematic structure provides a higher transmission ratio, thence a larger workspace and in principle higher speed at the TCP.

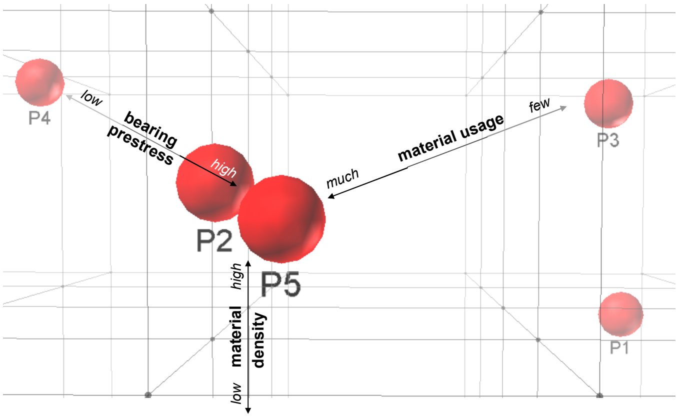


Figure 5. Visualisation of joint related properties

Figure 5 shows the joint related properties. The already described goal conflict between friction and clearance is observable in the visualisation, too. Furthermore, a loose cluster is made up of weight and angular movement against stiffness. The reason for this is that stiffness was considered to be realised by adding material, thence the joint becomes heavier and the moveable angles get smaller because of earlier collisions of the cranks. The distance between weight and angular movement can be interpreted as the usage of light-weight materials. To provide the same stiffness often more material of low density is needed than of high density.

By analysing figure 5 two research areas can be found. First, solve the goal conflict between friction and clearance, e.g. by developing joints with an active adaptability. Second, find low-weight joint structures that provide the same stiffness and moving angles, e.g. by investigating different topologies and new materials.

4. Conclusions and Outlook

On the basis of the product parallel robot, it has been shown that the visualisation approach is a very helpful tool to illustrate complex relations in an easy and understandable way. Though, the visualisation leads to a loss of information about interdependencies it is a very helpful basis to discuss possible product strategies with a potential customer. In contrast to existing multiple attribute decision making methods (e. g. utility analysis), the visualization method allows to easily consider and handle interdependencies between criteria. However, existing methods trying to solve decision making tasks with interdependent goals (e. g. Pareto Optimization) call for exact mathematic models of the decision problem. Those kinds of models can only be given in some areas in late design stages. Therefore, the presented method closes a gap by allowing to handle decision making problems with several interdependent criteria based on qualitativ information. Furthermore, the holistic visualisation of interdependencies leads to a deeper understanding of the regarded development task and therefore delivers impulses for important research work trying to solve basic goal conflicts.

In later phases of the design process more precise modelling of relations should be undertaken One approach is, first to structure and classify requirements as well as relations. Second, to model them within system context by using standardised notations like SysML (and specific extensions). This allows cooperation, automation in analysis, and efficient change- and optimisation-management.

Within current works, a methodical support to fill the correlation matrix is developed in order to reduce the risk of processing meaningless or wrong data in the visualisation tool. However, complex relations according to the state-of-the-art of different experts have to be analysed while creating the database. So, the wish to visualise relations forces the experts to analyse relations first, otherwise the underlying database gets too uncertain.

Furthermore, a consistency check which allows analysing the instinctively made statements should be established. For instance, the influence within one row must be comparable, i.e. question if the influence P1P5 (-5) was really bigger than P1P3 (-3). In addition, if there were direct relations P5P6 (supporting) and P6P7 (conflicting), could the indirect relation P5P7 yield formally (support + conflict = conflict) or would there be a new stronger influence leading to a different assumption.

In addition a sensitivity analysis should be made to discover the impact slight uncertainties have on the final visualisation.

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Dipl.-Ing. Carsten Stechert
Research assistant
Technische Universität Braunschweig, Institute for Engineering Design
Langer Kamp 8, D-38106 Braunschweig, Germany
Tel.: +49 (0)531/391-3349
Fax.: +49 (0)531/391-4572
Email: stechert@ikt.tu-bs.de
URL: http://www.ikt.tu-bs.de