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# A GENERAL FRAMEWORK FOR AUTOMATED CONCEPTUAL DESIGN OF ONE DOF MECHANISMS

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## Abstract

This paper describes an assistance tool created for those who have to design one degree of freedom mechanisms. It focuses on the conceptual design phase of finding a kinematic structure able to fulfil the requirements. The role of the assistance tool is to create the whole set of feasible solutions and to suggest those most relevant to the designer.

Current commercial tools are of assistance in building 3D models of mechanisms already defined by the designer and in processing a kinematical analysis from these models. The tool presented in this paper is directed rather towards the synthesis of mechanisms by providing a set of potential solutions and automatically building a simplified 3D model of each of these.

*Keywords: Early phases of design, Optimisation techniques, Layout design, Computer-aided design, Mechanisms*

## 1 Introduction

The design process consists of several steps. Once the requirements for a new product have been identified, the first step, generally called “conceptual design” [1] can begin. The main difficulty for the designer during this first step is to find a set of potential structures capable of handling the problem. Moreover, it is essential to find solutions which are technically and economically satisfactory. As the final performance and costs are strongly linked with the choices made during the conceptual design step, it would be useful to facilitate these choices through a systematic and automated method for conceptual design. The use of computer tools seems to be advantageous. Unfortunately, there are currently no commercial tools, as far as we are aware, designed to assist the conceptual design step. The tools available to the designers allow them to build 3D models of structures which have already been defined, and to process kinematic analysis from these models.

The literature provides several general computational methods dealing with conceptual design. All these methods are oriented towards the synthesis of mechanisms. Buchsbaum and Freudenstein [2] have identified two levels of synthesis:

- Structural synthesis, whose role is to find and build kinematic structures suitable for dealing with the problem. Two different synthesis approaches are used: the first, based on graph theory [2], [3] is appropriate for use with computational methods, but the relationships between graph and structures are not easy to establish. The second, based on qualitative reasoning and constraint programming directly provides potentially acceptable structures ([4], [5] and [6]). They proceed by automatic combination of elementary mechanical blocks (i.e. basic elements such as gears, rack-and-pinion, eccentric, slider crank, etc…).

- Dimensional synthesis. The goal is to find the main dimensions of a given structure to fulfil the necessary requirements. Research here is mainly concerned with linkage mechanisms [7].

At present, the proposed methods do not consider the possible extension of structural synthesis to the dimensional synthesis. This paper presents a method linking directly the two synthesis phases and working in a unified framework.

# 2 Main characteristics of the proposed method

## 2.1 The general framework

The goal of the proposed method is the automatic creation of all the kinematic structures likely to satisfy a given specification sheet. Specifications can include both geometric requirements, such as the position of the output shaft relative to the input shaft, and functional requirements, mainly the definition of the output motion of the designed mechanism.

Our method concerns mechanisms with a single input and a single output (SISO). In addition, it is restricted to mechanisms transforming a uniform rotational motion into a uniform (rotation or translation), reciprocating or oscillating motion. Only mechanisms powered by an electrical source (i.e. an electric motor providing a uniform rotational motion at the mechanism’s input) are considered. Moreover, mechanisms concerned are all defined as closed loop kinematic chains with one degree of freedom.

## 2.2 Some initial choices

Firstly, the concept of Elementary Mechanical Block (EMB) has been adopted. A database containing 39 EMBs has been defined. The work of synthesis presented below proceeds by combination of these EMBs. Figure 1 shows 8 EMBs extracted from this database. The EMBs used are representative of classical mechanical elements such as spur gear, worm gear, rack and pinion, eccentric, slider-crank, etc…

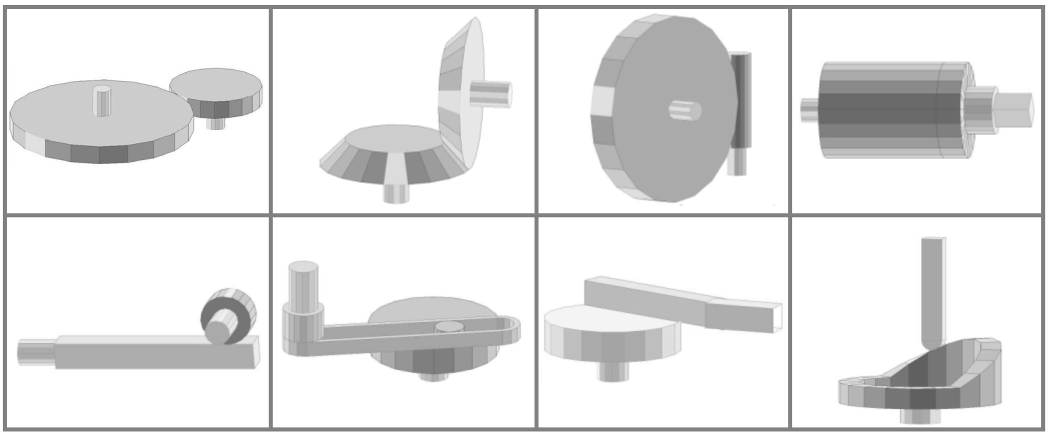


Figure 1. Some mechanisms drawn from the EMBs database

The principle of automating the synthesis process has been chosen. The designer may control the activity during all the steps, but his contribution is restricted to the definition of input data.

Our approach is based on the utilisation of optimisation algorithms. To be efficient, the assistance method must be able to provide the most appropriate structures with their optimal configuration. In order to define accurately all the characteristics of these structures, determinists optimisation methods, such as the Augmented Lagrangian method, has been selected.

## 2.3 The synthesis process

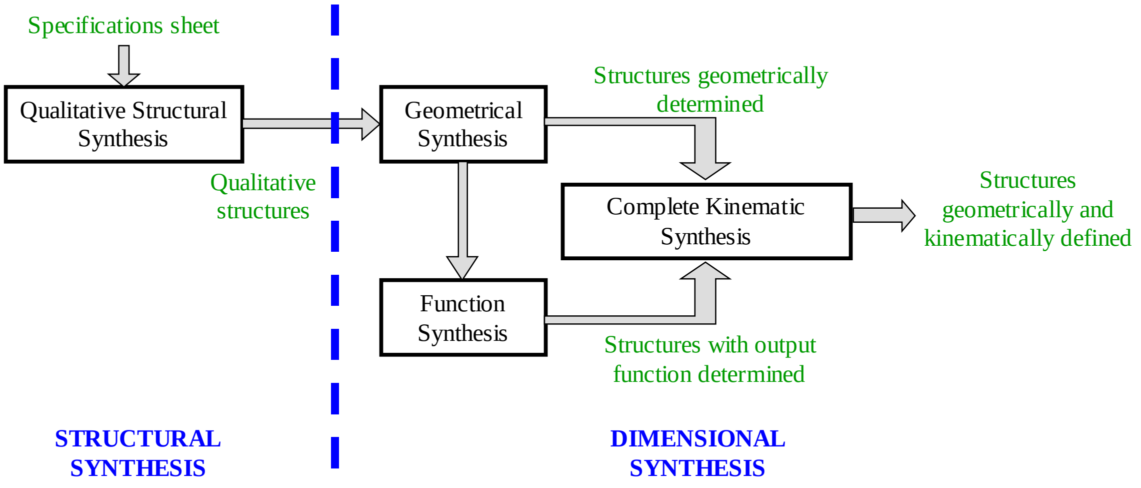



Figure 2. Flow chart of the assistance method

Figure 2 gives the flow chart of the synthesis process that consists of two main steps:

- Step 1: structural synthesis. This step uses qualitative reasoning. Only global information about the expected mechanism is used at this time. This step generates a set of qualitative structures which satisfy the requirements, as far as qualitative criteria are concerned. Structures are sorted in order to select the most appropriate according to the designer criteria.

- Step 2: dimensional synthesis. An optimisation approach is used to provide a more accurate definition and evaluation of the potential solutions. The additional data taken into account during this step is related to the problem geometry and the output function required. As qualitative reasoning is insufficient, the problem becomes one that deals with dimensions. The use of optimisation techniques to solve directly the whole synthesis problem may lead to inaccurate results because the problems are highly non-linear. So the step has been divided into three tasks in order to make a more progressive synthesis approach possible.

In addition, a 3D model is built at the end of the qualitative step. Each potential solution is a combination of Elementary Mechanical Blocks (EMBs) and the 3D model is obtained by connecting the various EMB parametric models. This representation becomes more precise during the optimisation step and the 3D model is updated at the end of dimensional synthesis.

# 3 Qualitative structural synthesis

## 3.1 Principles

This step creates a set of qualitative structures. Figure 3 illustrates the method used. Once the requirements have been identified (output motion type, transformation ratio between input and output motion, input and output member orientation, reversibility…) the work of synthesis can begin. Five successive tasks are undertaken.

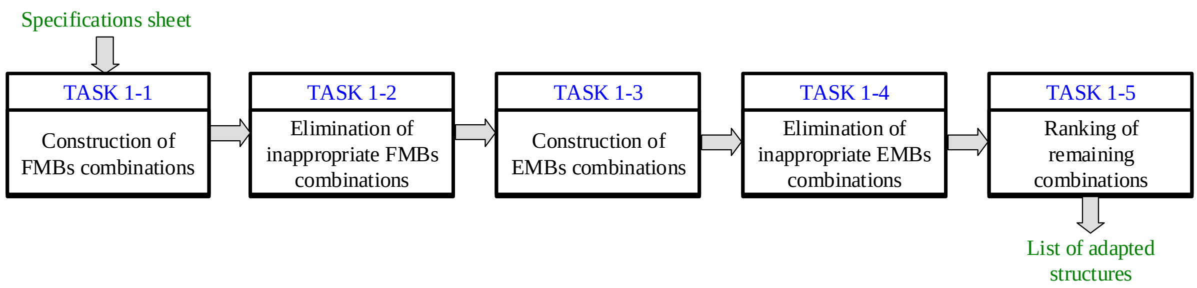



Figure 3. Flow chart of the qualitative structural synthesis step.

Tasks 1-1 and 1-2 use the concept of Functional Mechanical Block (FMB). Some authors calls this concept “Abstract mechanism” [5]. Each FMB is defined by an input and an output type. Task 1-1 proceeds to create all the possible FMB combinations compatible with the requirements and kinematically valid, restricted to a maximum number of serially connected FMBs. The result of this task is a list of valid FMB combinations. Task 1-2 eliminates from this list combinations that are of no mechanical interest (e.g. eliminates combinations providing important inertia effects) by using a set of predefined rules. The designer can choose whether to activate or inactivate each rule.

The following tasks 1-3 and 1-4 are held on the EMBs level. Each FMB is connected to the list of EMBs which represent all the possible implementations. Task 1-3 enumerates all the possible EMB combinations drawn from the available FMBs combinations. Then, considering a new set of rules, task 1-4 eliminates the inappropriate EMB combinations. Qualitative considerations are taken into account by these rules, such as the ability to produce the required motion, to obtain the required transformation ratio, to respect a minimal level of efficiency…

Task 1-5 objective is to rank the remaining structures in order of appropriateness according to the designer criteria. To achieve this, each EMB is evaluated according to economic and technical criteria. Each combination is made up of an association of EMBs, so the rank of a structure is defined by the average of its EMB criteria weighted by coefficients given by the designer.

## 3.2 Results

Let us consider the case of a car windshield wiper mechanism. Requirements concern the output motion, as an oscillating motion with a 120 degrees stroke and a period time of 1 second. The input speed is 2500 rpm. Input and output members must be parallel. The mechanism should also be irreversible. Results are ordered as a list of solutions, each line corresponding to a structure. 3D models are available and represent structures (that are associations of 3D EMB models). Nevertheless, dimensions of these models are not linked to the requirements. These are just default dimensions.

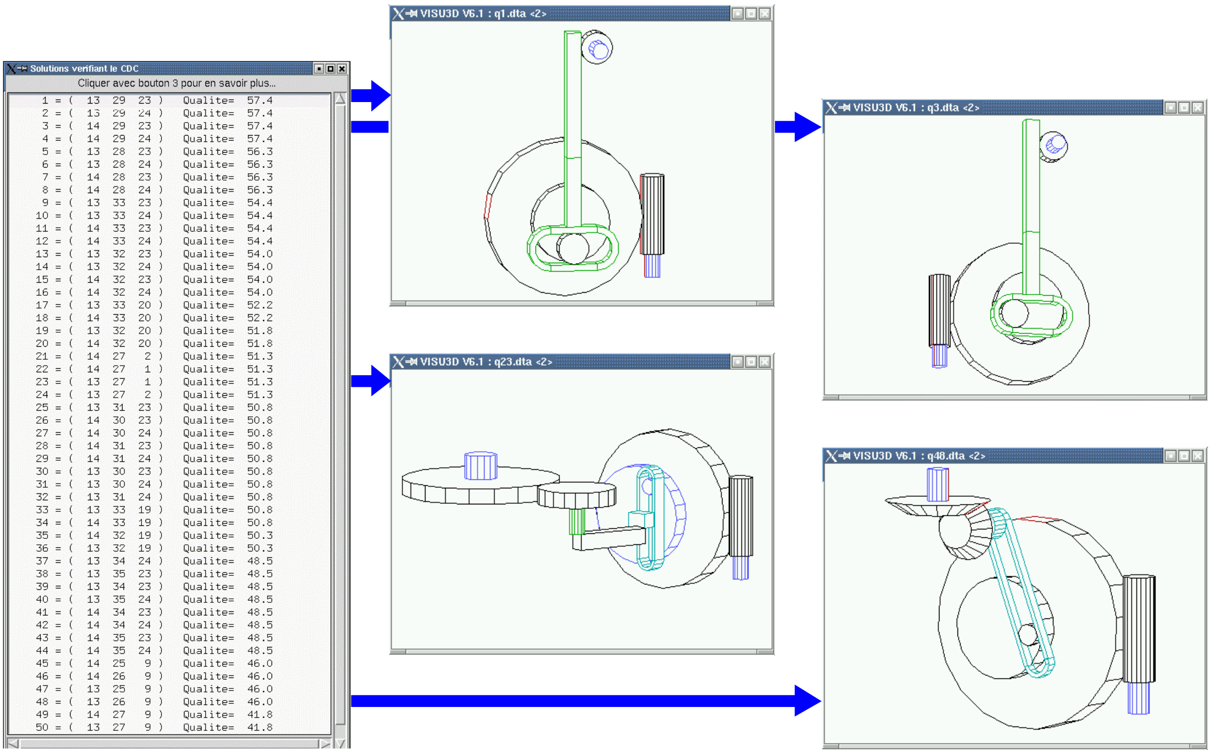



Figure 4. List and representation of a part of structures proposed at the end of qualitative synthesis step.

For the example studied, results given by the qualitative structural synthesis step are illustrated on Figure 4. With a maximum number of 3 connected EMBs in a combination, 50 structures qualitatively satisfy the requirements. Some of the proposed structures are close to those used industrially (structures at the top of Figure 4), but others also present a mechanical interest (e.g. the two structures at the bottom of Figure 4 that only use rotational motion throughout the combination).

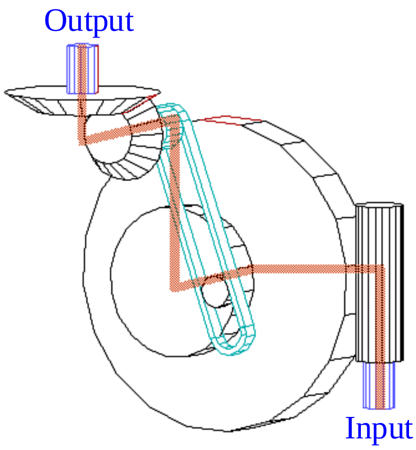
# 4 Dimensional synthesis

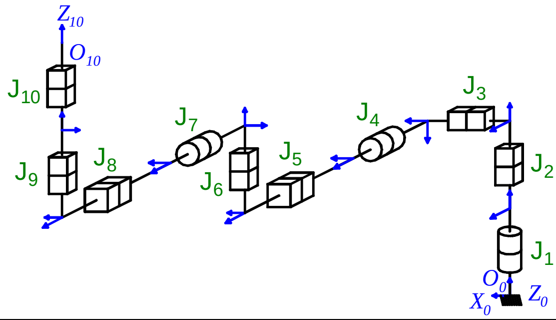
Structural synthesis enables a set of structures to be established. To define these structures precisely, it is essential to define their main structural dimensions. The 3 tasks presented below ensure that this definition is carried out correctly.

## 4.1 Geometrical synthesis

The problem to solve here is to find the appropriate parameters for a structure in order to obtain the required geometry. Requirements concern positions and orientations of the input and output member and the overall size (defined as a paralepipedic envelop) in which the mechanism must be contained.

In order to facilitate this task, the notion of skeleton is introduced. The skeleton of a structure is obtained by eliminating all volumes from the parts of the structure and retaining only elements which play a role in the geometric definition of the structure. Moreover, a geometric model is linked to the skeleton, represented henceforth as a sequence of prismatic and rotational joints. It uses the well known modified Denavit-Hartenberg model, widely used in robotics, which allows us to perform an automatic procedure for geometric model construction. Indeed, each EMB is associated with a skeleton and its corresponding geometric model. The global geometric model is built by the addition of the elementary geometrical models. Figure 5 represents the skeleton, the geometrical model and the parameter table associated with a structure.




| | $J_1$ | $J_2$ | $J_3$ | $J_4$ | $J_5$ | $J_6$ | $J_7$ | $J_8$ | $J_9$ | $J_{10}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $\sigma_i$ | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 |
| $\alpha_i$ | 0 | 0 | $\pi/2$ | $\pi/2$ | 0 | $\pi/2$ | $\pi/2$ | 0 | $\pi/2$ | 0 |
| $a_i$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $\theta_i$ | $q_1$ | $\pi/2$ | $\pi/2$ | $q_4$ | $\pi/2$ | $\pi$ | $q_7$ | $\pi/2$ | $\pi$ | 0 |
| $r_i$ | 0 | $q_2$ | $q_3$ | 0 | $q_5$ | $q_6$ | 0 | $q_8$ | $q_9$ | $q_{10}$ |

Figure 5. Skeleton, geometrical model and parameter table of a structure.

The synthesis problem thus becomes an optimisation problem. As the geometric model input is positioned like the required input, the optimisation problem consists in finding appropriate parameter values to make the geometric model output and the required output coincide, while the entire geometric model lies inside the specified envelope. The optimisation problem is expressed like this:

- Variables: those associated with the geometric model (expressed as $q_i$ in Figure 5).
- Constraints: constraints linked to the output member orientation and position, constraints relative to the positioning inside the envelope, and finally bounds of variables, fixed with technical and geometrical criteria or with constraints linked to the requirements.
- Objective: this kind of synthesis problem is generally redundant (in view of the high number of joints). As the number of solutions is often infinite, an optimisation criterion has been chosen to find a more suitable solution. As designers often prefer compact mechanisms, we have decided to minimize the overall length of the skeleton, expressed as the sum of prismatic joint lengths.

An algorithm has been implemented to build, for each qualitative structure, the optimisation problem and then to solve it. A strategy is used to determine automatically initial values of variables. The interested reader will find additional information in [8] and [9]. At the end of the optimisation algorithm, either a solution exists and a satisfying layout is given, or no solution exists, in which case the studied structure is eliminated.

## 4.2 Function synthesis

During the geometrical synthesis, requirements concerning the output motion are only partially used (with the use of the output stroke as a bound for some geometric model variables). The function synthesis consist in finding the kinematic parameter values in order to produce, as closely as possible, the motion required. It is applied to every structure that has satisfied the geometrical synthesis task.

To succeed in this task, it is essential to construct the input/output mechanism equation. We will take advantage of the fact that the structures are obtained from an association of EMBs. Indeed, for each EMB, a I/O relationship is available. The construction of the global relation can be therefore processed by combining these elementary relations. Equation (1) shows an I/O relationship for a structure listed in the table at Figure 4.

$$M_o = -x_5 \times \left(x_3 \times \cos\left((M_i/x_1) + x_2\right) + x_4 \times \sqrt{\left[1 - \left(\frac{x_3 \times \sin\left((M_i/x_1) + x_2\right)}{x_4}\right)^2\right]}\right) + x_6 \quad (1)$$

Thus, the synthesis problem becomes a function generation problem, and is again treated as an optimisation problem, with:

- Variables: those linked with the EMBs I/O relations. Additional variables, such as $x_2$ and $x_6$ in eq. (1), called offset variables are used to increase the ability to fit the requirements.

- Constraints: constraints are relative to the respect of the transformation ratio and to obtaining the stroke required (with a level of tolerance). In addition, some constraints linked to the EMBs used are introduced in order to avoid the appearance of incoherent configurations (for example, the length of the slider should not be less than the crank radius when considering the slider-crank EMB).

- Objective: the criterion used is a least square criterion between the function required and the function generated (both defined through a set of points).

An algorithm ensures the automatic construction of the global I/O relation, the construction of the optimisation problem and then its solution. A specific procedure ensures the choice of different starting points for the problem variables while avoiding the risks of obtaining a local minimum for the objective (this kind of difficulty is inherent in the use of determinist optimisation algorithms when periodic functions are used).

## 4.3 Complete kinematic synthesis

Geometrical and output function requirements have been considered separately. So, on the one hand, the geometrical synthesis has defined the most compact structure, and on the other hand, the function synthesis has provided the nearest possible output function to the function required. To complete the dimensional synthesis step, it is essential to consider both aspects simultaneously.

In fact, geometrical and kinematic parameters are linked. These links could be expressed as constraints between these parameters. As an example (see Figure 6), a constraint exists between the length of a skeleton part and the slider and crank lengths of a slider-crank mechanism.

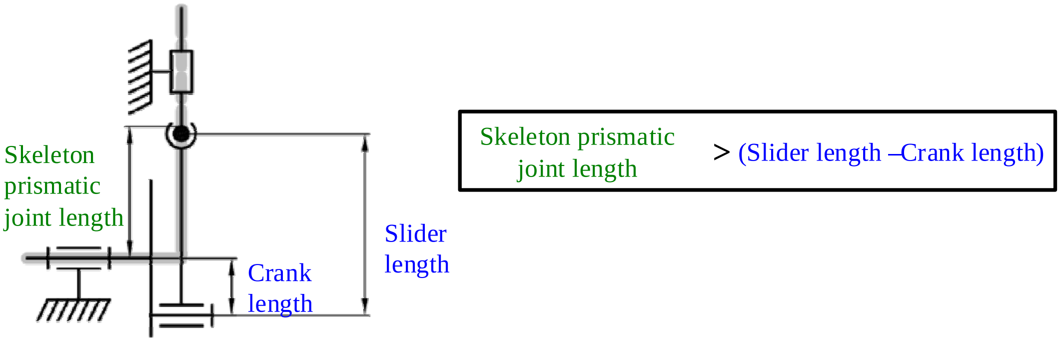



Figure 6. An example of the relationship between geometrical and kinematic parameters.

These new constraints are added to the constraints linked to geometrical synthesis and function synthesis. These new constraints are first checked with the dimensions defined before. If constraints are not violated, this means that the two optimal solutions available from the previous tasks are compatible. Otherwise, a new optimisation problem is considered. All variables and constraints defined until now are concerned. The objective used (which stays mono-objective) depends on the designer's choice. It can be the minimisation of the skeleton length or the precision of the output function produced.

## 4.4 Results

At the end of dimensional synthesis, mechanisms have their main dimensions accurately defined. For the example introduced in 3.2, the improvements in structure definition are significant (Figure 7). 3D models from the structures can now be processed in the appropriate configuration. Moreover, the function produced is also the nearest possible to the one required. However, some dimensions remain undefined (for example gear thickness). In order to make our 3D models easier to understood, these one are fixed by using parametric relations with geometrical and kinematic variables.

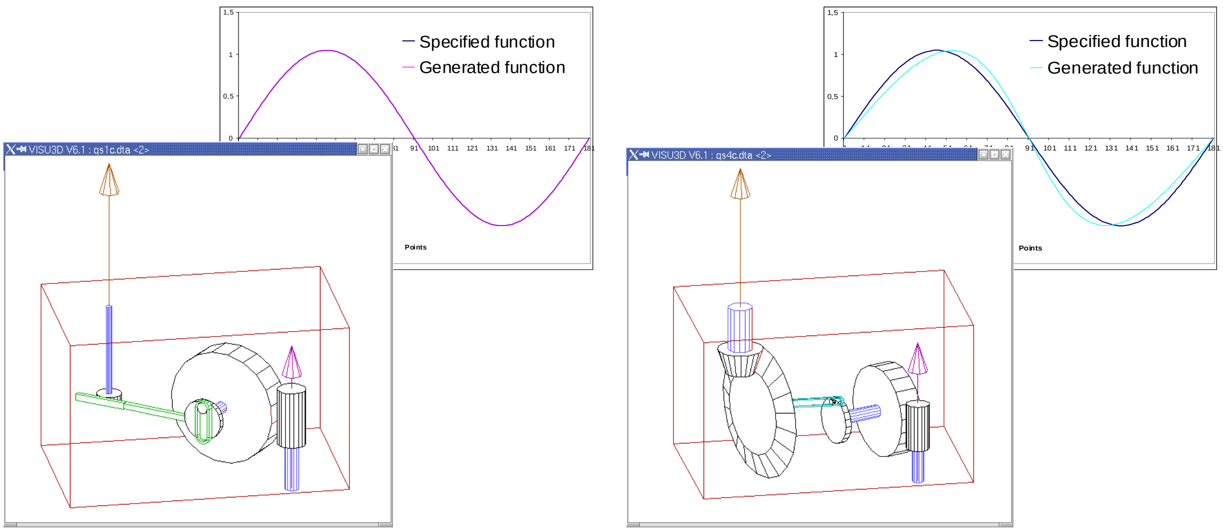



Figure 7. Results at the end of step 2 for 2 candidate structures

# 5 Development of a software tool

Implementing the synthesis process has enabled us to develop a software tool called ACoDeM-1 (for **A**ssisted **Co**nceptual **De**sign of **M**echanisms with **one** degree of freedom), which can be operated using Linux exploitation system. All the interfaces have been developed with Tcl/Tk script language. Computational tasks are programmed in C ANSI. A graphic and animation tool that allows us to use a specific and well adapted file format has been also incorporated.

# 6 Example: Design of a hardness tester mechanism

Let us consider the case of a hardness tester mechanism. The goal is to produce a reciprocating motion with a 30 mm stroke. The output function required must be the nearest possible from a smooth trapezoidal function (see Figure 8). Output period time is equals to 60 seconds. The input motion is a 1500 rpm rotational motion.

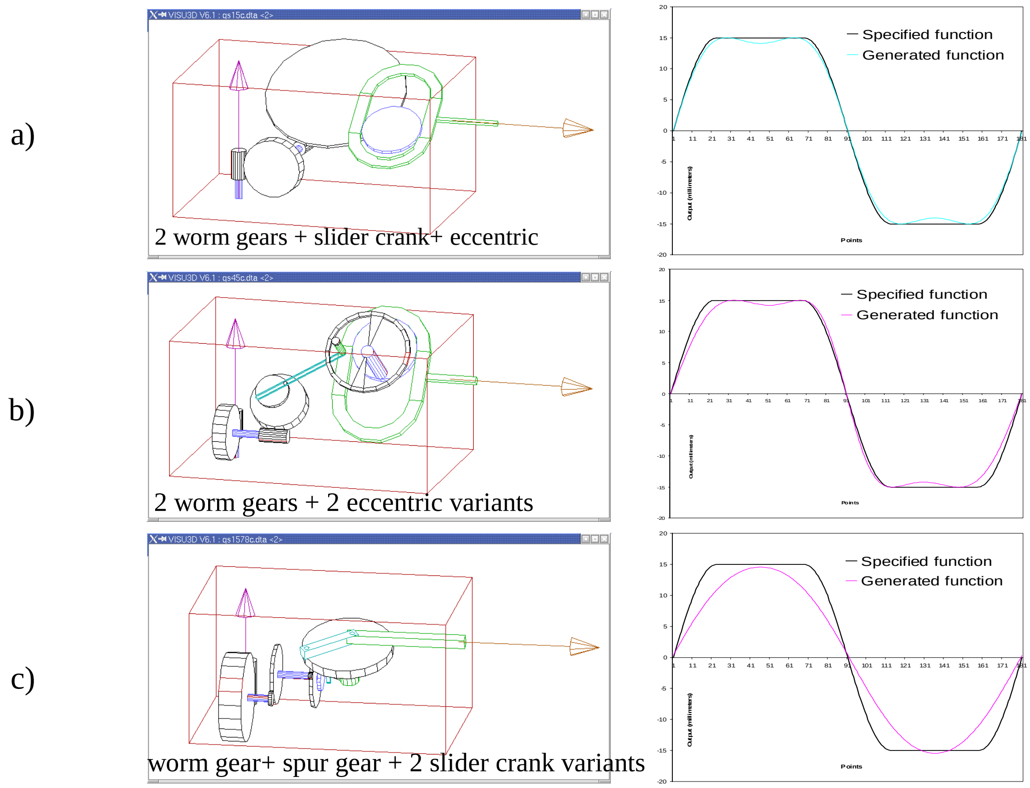



Figure 8. 3 structures proposed by the assistance tool and their corresponding output function

Structures obtained at the end of qualitative step are numerous (around 20000, when using a maximum of 4 EMBs serially connected). The dimensional synthesis step allows to eliminate inappropriate solutions and to rank the 4225 remaining structures, the most significant criteria being the output function produced. Three structures are described in Figure 8. Their 3D representation and their output function are given. Structure in Figure 8a is ranked 15$^{th}$. The function generated is among the best ones fitting with the requirements (right side of Fig. 8a). Progressively, structures ranked in lower places have their output function that moves away from the required one. The structure in Fig. 8b is ranked 45$^{th}$ and the one represented in Fig. 8c, that do not presents a great interest is ranked 1578$^{th}$).

# 7 Conclusion

A fully automated approach to the drawing up of a set of kinematic structures is proposed. Its main advantage lies in the fact that possible solutions are submitted for the designer's appreciation instead of being created by the designer. Solutions are ranked according to how well they fulfil the designer criteria and are presented through a 3D graphic interface that allows fast and easy examination of the proposed structures. The tool provides a larger number of solutions for a given problem than conventional design methods which are generally limited by the designer's creative skills.

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