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DEVELOPMENT OF A REPRESENTATION SCHEME FOR THE APPLICATION OF GENETIC METHODOLOGY TO FUNCTIONAL DESIGN

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Abstract

The modeling strategies proposed for high level conceptual design stage in literature are limited to developing a formal description way of designed artifacts. Although, they are very useful in archival and transmittal of design information, they do not assist the generation of the novel designs.

In order to reach previously undiscovered results, an evolutionary methodology could be the expected solution. Evolutionary methods do not only deal with the optimization of the result but also offer new alternative solutions to the problem. For this purpose, in this paper a suitable representation scheme for the application of genetic methodology to artifact design at functional level is developed. In addition to this, to generate new alternative solutions, a crossover operation is defined.

Keywords: Genetic Design at Conceptual Level, Functional Modeling, Design Automation

1. Introduction

Conceptual design stage, which comprises the determination of the customer needs, the clarification of the task and the search for the suitable solutions, is the most important part of the product design and development period. In this stage, a complete sketch of the product, which will satisfy the identified customer needs, is developed without considering detailed calculations and technical drawings. Therefore, designers should have to make large number of decisions and compare hundreds of alternatives.

In literature, two design strategies are developed to systemize the conceptual design phase. These are bottom-up and top-down design strategies. The traditional approach, using bottom-up strategy, forms the products in physical domain. In this approach, the products are developed by getting together the physical modules and components. While this methodology searches alterative solutions in physical domain, a search for solutions in functional domain is not performed. As an advantage, this method always reaches a physically realizable solution but this solution may not always be the most efficient one.

However top-down design strategy looks for a solution in functional domain, before investigating physical solution alternatives. Likewise there can be different physical solutions for a determined functional solution, a specified customer need can be satisfied with different functional solutions [1]. Therefore, the form independent approach provides the designer with flexibility in physical design domain. However in this method there is no guarantee that all derived solutions are always physically realizable. In this approach, the generation of physically realizable functional solutions highly depends on the past experiences and prejudices of the designer.

Generation of previously undiscovered designs is not possible only by the manipulations in physical solution space. In many cases, although the advances both in hardware and software technologies create variety in designs, these new designs becomes functionally equivalent of their initial prototypes. The creativity needs changes in functional space. Even though it is not difficult to create different functional solutions for a design task, many of them can be physically unrealizable solutions. Therefore, the search strategies such as breadth first and depth first searches in functional domain need supervising to avoid creating physically impossible solutions. Moreover, both the physical and functional solution spaces present infinite configurations. Hence, these search strategies are very time consuming and in many times practically inapplicable.

At this point, top-down design approach needs an effective modeling strategy. In literature, there are numerous attempts for developing a functional modeling strategy for system design. However, many of these attempts are limited to developing a formal way to describe the product. Developing a strategy not needing a human designer is very important for the computer implementation of the engineering creativity. This strategy should guide the search in functional solution space and offer new alternative solutions.

For this purpose, an evolutionary strategy (based on Genetic Algorithms and Genetic Programming) can be applied to conceptual design stage. Application of this evolutionary strategy needs standard representation of the problem and an evaluation criterion for the developed solution alternatives.

An evolutionary strategy has the advantage to create novel designs without requiring understanding of procedures used to generate them. It only requires the representation of the structure and an evaluation function to determine the quality of generated structures. This feature makes the strategy computer implementable. Moreover, not being founded on understanding of procedures makes the methodology domain independent and applicable both for functional and physical design issues.

In literature, many applications of evolutionary design strategies to the physical design tasks are available [2]. However, a methodology called Genetic Design (GD) [3] provides a powerful tool to aid the designer by generating viable artifact design alternatives for further consideration. Roston G. P. claims that this strategy can apply all stages of design procedure. The only need for this application is the development of a suitable representation scheme for that stage and finding an evaluation criterion to compare designed artifacts.

This study mainly focuses on the application of GD strategy to functional level conceptual design phase. In this paper, development of a representation scheme for high level design issues is presented.

In the remainder of this paper, section two describes a representation scheme suitable for genetic design methodology at high level (functional level) conceptual design of systems. In section three, a case study for the application of developed representation scheme is presented. Section four provides an example for the application of genetic operations and development of an evaluation metric is discussed in section five. Finally, the conclusions and future works are given in section six.

2. Development of a Representation Scheme at Functional Level

In artificial evolution, the biological terms genotype and phenotype are usually employed [2]. Genotype is the "internally coded, inheritable information" carried by all living organisms. Simply it is the coded representation of the individual. In biological systems, it usually corresponds to DNA [2]. Phenotype is the "outward, physical manifestation" of the organism. These can be the physical parts, atoms, molecules, structures, metabolism, tissues, organs; anything that is part of the observable structure of a living organism [4].

Genetic Algorithms use the populations of genotypes consisting of strings of binary digits or parameters. These are read to produce phenotypes [2]. In GA, the chromosome is not the artifact itself, but rather the encoded representation of it [3]. It should be translated to involve genetic operations. However, in GP the artifact itself (phenotype) is represented by a tree structure. The genetic operators operate both on the structure of the tree and the numeric values found at the leaf nodes [3].

In GD methodology, GD prefers GA approach in development of representation scheme and uses genetic manipulations of GP. In other words, in GD methodology, the chromosomes are the encoded representation of individuals. In Roston's GD applications, this representation scheme is the hierarchical physical resolution of the artifact. However, in our study, functional representation of the artifact is preferred.

The representation scheme used in GD for functional design is rooted tree. A rooted tree consists of terminals and functions appropriate to problem domain. As the functions become the internal nodes, the terminals are the leaf nodes in the tree structure. In order to be able to construct the tree structure of the artifact, domain specific function and terminal definitions must be performed.

2.1 Function Definitions for High Level Design

In the study of (Stone R.B., et al) [5] on functional dependencies, function chains are examined under two main titles. These are sequential function chains and parallel functional chains. In *sequential function chains*, the sub-functions must be carried out in a specific order to generate the desired result. Sequential functions use the output flow of previous function as input flow. *Parallel function chains* comprise sets of *sequential function chains* sharing one or more common flows. Parallel functions use the same flow as the input but can create different output flows. Figure 1 and Figure 2 illustrate examples for sequential and parallel function chains respectively.

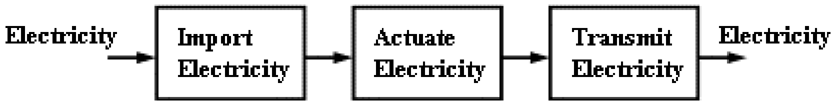

Figure 1. Sequential function chain.

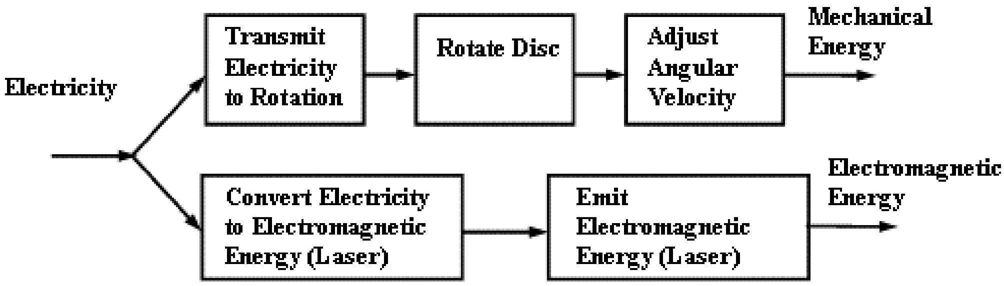

Figure 2. Parallel function chain.

Due to this classification, functions of GD representation are determined as SEQ, which represents sequential, and PAR, which represents the parallel. These two functions configure the terminal set in the tree structure.

2.2 Terminal Definitions for High Level Design

Terminals of the GD representation are the operations, which are performed by the designed artifact, to obtain the desired output flow from available input flows. In high level design, these are the black box representation of the artifact functions such as "convert electrical energy into mechanical energy".

In order to obtain a formal grammar, reconciled functional basis developed by (Stone R. B., et al) [6] is proposed as the terminal set of GD. The aim at the development of this basis is to obtain a complete set of function and flows that covers the whole systems and products in functional domain. This basis provides the designer with a standard language for the description of artifacts.

Reconciled functional basis groups the functions under eight classes. These are *branch, channel, connect, control magnitude, convert, provision, signal and support*. All of these functions are broken into secondary and tertiary levels. The degree of specification increases with the level that function takes place. In the same manner, reconciled functional basis describes the flows under three major classes. These are *material, signal and energy.* These classes are also broken into secondary and tertiary levels. The detailed set of function and flows was published in [7].

In order to define a terminal node, *verb-object* representation is used. In this representation, verb part indicates the function and object part specifies the flow descriptor such as "import electricity" or "guide particles". Both of the function and the flow can be selected from any of the three levels depending on the specification desired. After the definition of the terminals, these terminals are placed as leaves of a rooted tree structure. As an example, the tree representation of a CD player is given in the next section.

3. A Case Study: Tree representation of a CD player

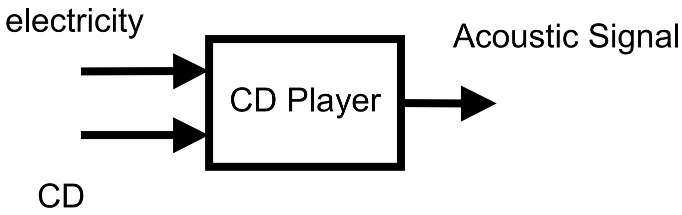

Figure 3. Black Box representation of CD Player.

In Figure 3, black box representation of a CD player is illustrated. The internal operations to obtain acoustic signal flow as the output are the terminals (i.e leaf nodes) of the rooted tree structure. This representation of a CD player is given in figure 4.

SEQ function at the root of the tree states that all the sub-functions are sequential. This means that all sub-functions should accept the output flows of previous functions as their input flows.

The first sub-function is again sequential. It is the supply electricity module of the device. The input flow of the first terminal in the first sub-function should be one of the available input flows. In this example, "electricity" is the input flow of our system. Throughout the first sub-function, import, actuate and transmit operations are performed on electricity flow. Hence, the output of the first sub-function becomes electricity.

The second sub-function is parallel. Due to being of this sub-function sequential to the first sub-function, it has to use the output of the first sub-function (electricity) as input flows in both of its parallel terminal sets. This means that both "convert electricity to rotation" and "convert electricity to electromagnetic energy" terminals accept "electricity" as their input flows. The first sequential chain of these parallel terminal sets converts electricity to rotation (mechanical energy), rotates disc (CD) and adjusts the angular velocity of the CD. Therefore the output of the first sequential chain is mechanical energy (angular velocity of disc). The second sequential chain converts electricity to electromagnetic energy (laser) and sends (emits) laser to the disc surface. As a result, the output of the PAR sub-function is the reflected electromagnetic energy (reflected laser beam) from the disc surface.

The next sub-function is sequential. It collects the reflected beam (electromagnetic energy), compares the energy and generates binary signal. Finally, the last sub-function is again sequential. It converts the digital data to analog, amplifies it and exports acoustic signal.

In this representation scheme, in order to construct a syntactically correct configuration, all sequential and parallel modules should be placed in correct order. This order is determined by the output flows of the modules. This requirement violates the closure property of genetic programming representation. To correct this deficiency, a variation of genetic programming called "strongly typed genetic programming" (STGP) is preferred. This representation allows defining some restrictions on function inputs. STGP representation also guarantees the generation of synthetically correct offsprings at the end of genetic operations.

4. Applications of Genetic Operations

Genetic Design starts with the initialization of the population. The next step is the evaluation of the individuals in the population. Regarding the results of this evaluation, reproduction operation is performed. After reproduction, crossover operation is applied and the next generation of the population is obtained. Until reaching the termination conditions, this procedure repeats itself.

In crossover operation, the most important thing that has to be considered is the input and output flow relations of the modules. In parsing operations of the trees, the inputs and outputs of the offsprings should be suitable to the order of flows in the new parents. In other words, only the modules, which have the same input and output flows, can be exchanged.

In figures 4 and 5, tree representations of two randomly selected parents, a CD player and an Optical Mouse are given. In order to be able to perform the crossover operation between these parents, the modules, which have the same inputs and outputs should be detected. The modules shown in the boxes with darker outlines have the same input and output. Both of them accept electromagnetic energy as input and generates binary signal as output. After the crossover operation of these modules, a child, which represents a new device, illustrated in figure 6 is obtained. This device is the primitive version of the optical mice, which are used today. In the original optical mouse technology, the mouse pad is a highly reflective surface and has a grid of dark lines. Each time the mouse is moved, the beam of light is interrupted by the grid. By comparing the reflected energy, a binary signal is generated and sent to PC.

By removing a rooted sub-tree from the first parent and inserting it to the crossover point of the second parent, a new functional solution for a computer input peripheral (pc mouse) is obtained. Although this is a very simple example, it gives an idea about the creativity of the genetic design methodology.

5. Development of an Evaluation Metric

Development of an evaluation metric is one of the future works of this study. However, at this point, the second axiom of the axiomatic design theory can be proposed as an evaluation metric for investigation [1].

As a summary, information axiom claims that there can be many designs, which are equally acceptable from the functional point of view. However, one of these designs may be superior to others in terms of probability of success in achieving the design goals as expressed by the functional requirements. The one with the highest probability of success is the best design. In order to reach the highest probability of success, the information content of design should be minimized. Information content of a design is a dimensionless quantity. Therefore, handling multiple objectives also becomes possible with a single evaluation measure.

However, calculation of information content requires the completion of the physical design of this artifact. Consequently, corresponding physical components of the defined functions should also be determined to evaluate the designs regarding to their information contents.

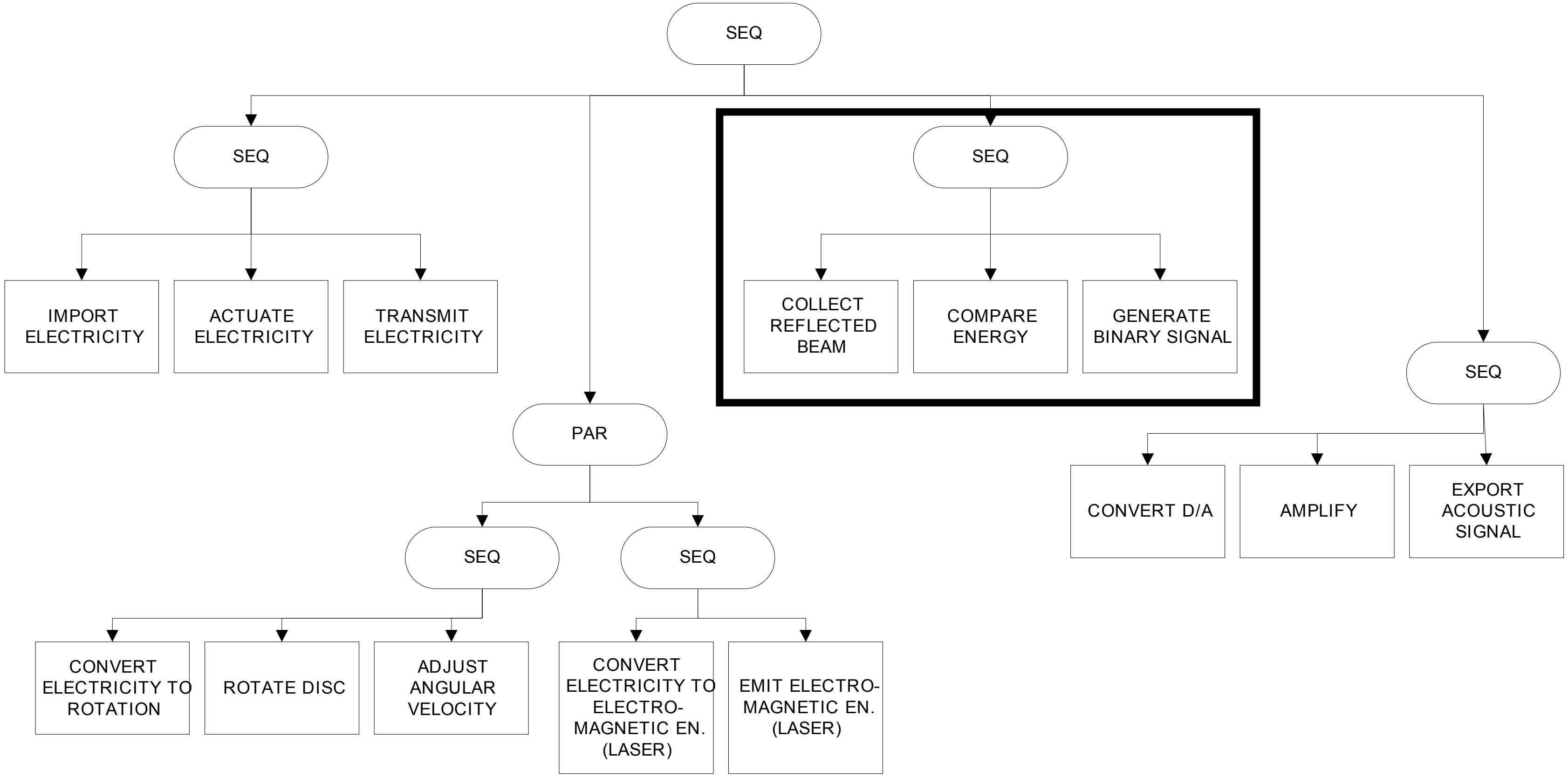

Figure 4. Rooted tree representation of CD player.

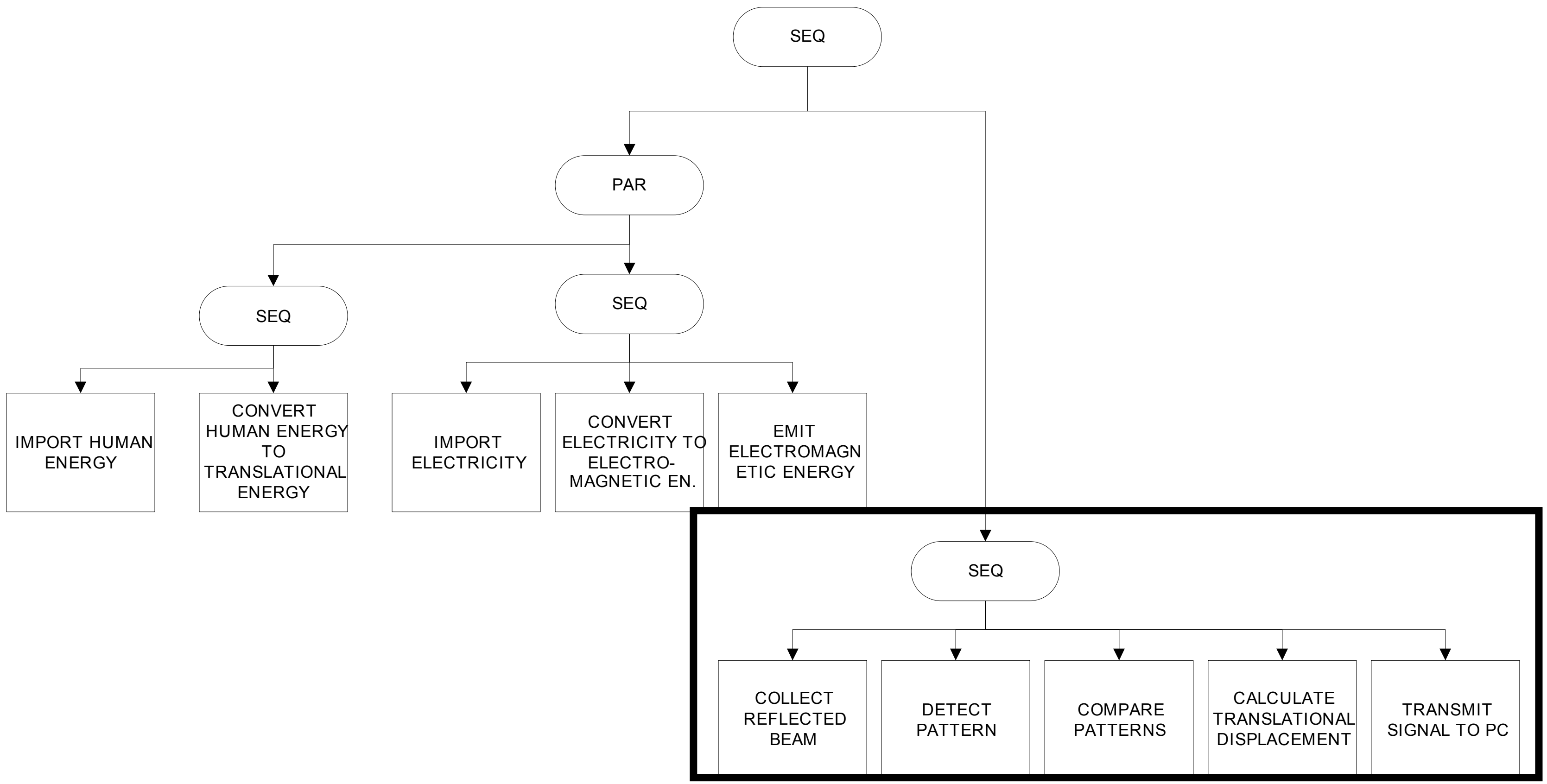
SEQ
PAR
SEQ
SEQ
IMPORT HUMAN ENERGY
CONVERT HUMAN ENERGY TO TRANSLATIONAL ENERGY
IMPORT ELECTRICITY
CONVERT ELECTRICITY TO ELECTRO-MAGNETIC EN.
EMIT ELECTROMAGN ETIC ENERGY
SEQ
COLLECT REFLECTED BEAM
DETECT PATTERN
COMPARE PATTERNS
CALCULATE TRANSLATIONAL DISPLACEMENT
TRANSMIT SIGNAL TO PC

Figure 5. Rooted tree representation of Optical Mouse.

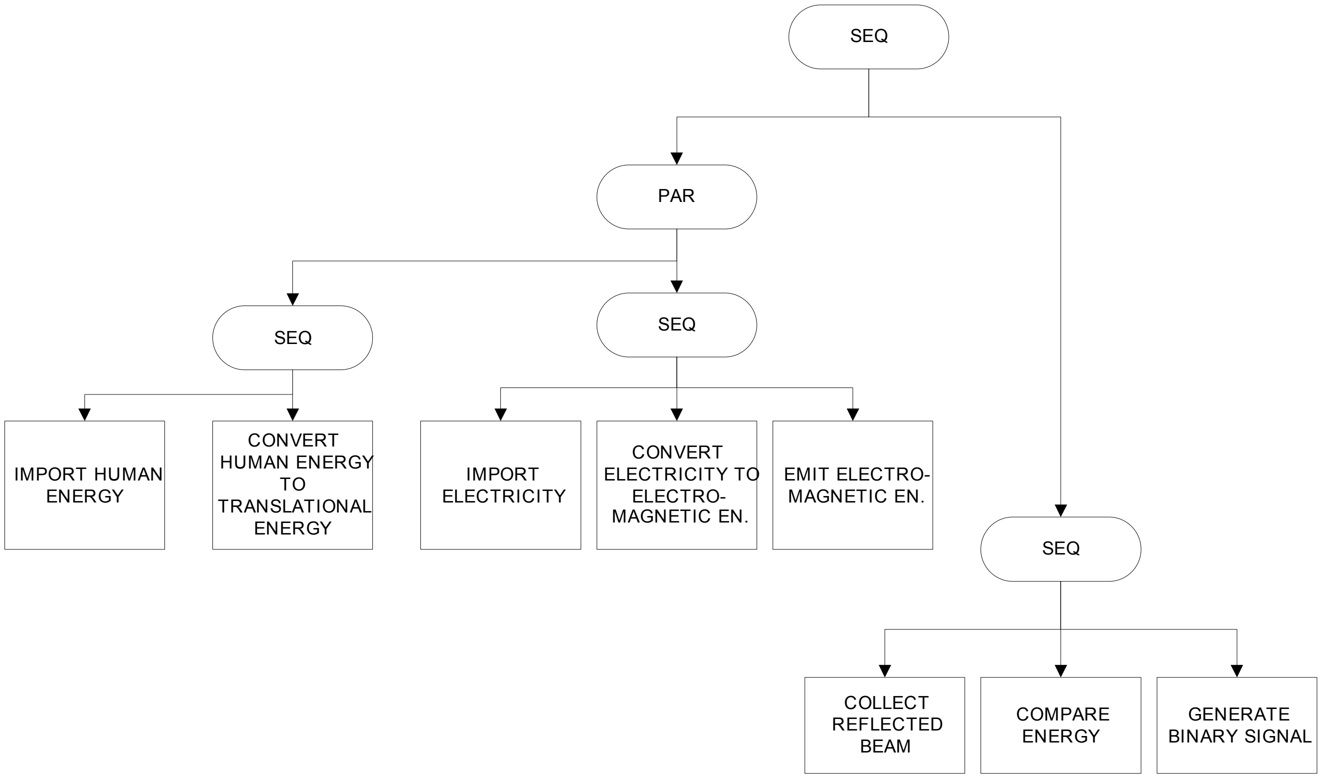

Figure 6. Rooted tree representation of Optical Mouse – CD Player Child.

6. Conclusions and Future Works

6.1 Conclusions

In this study, Genetic Design methodology for conceptual design stage is introduced. The selection of a formal grammar for high level conceptual design is performed. Moreover, construction of a representation scheme suitable for genetic operations is completed. The constructed scheme is suitable for "strongly typed genetic programming (STGP)" applications. Although the application of the STGP is more difficult, it guarantees the generation of the syntactically correct results.

A proposal is made for the development of an evaluation metric for generated solution alternatives. This metric is the second axiom of the axiomatic design theory. This axiom aims to minimize the information content of the design and therefore increases the probability of success. This evaluation strategy is also suitable to handle multiple design objectives.

A crossover operation is defined. This operation is suitable for defined representation grammar and at the end of crossover operation, new children are syntactically correct individuals.

With the development of an evaluation metric, the Genetic Design will have the ability to create new design alternatives and to evaluate them without help of human designer. With the completion of the theory, an important step will be taken in the automation of the conceptual design stage.

6.2 Future Works

In order to be able to perform the genetic operations, an evaluation metric should be developed. Automatic evaluation of the created design alternatives minimizes the dependency of designs to the designer's experience and the effects of designer's prejudices on design decisions.

The methodology should be tested with practical design applications. These tests will reveal the advantages and the drawbacks of the developed representation scheme and the evaluation metric. Moreover, these tests will give an idea about the ideal size of the initial population and the ideal crossover and mutation probabilities.

Finally, the computer implementation of this methodology should be performed at least for simple design applications.

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