Title:

Intelligent CAD with Conceptual Design, Embodiment Design, and Detailed Design Functions

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Introduction:

Design in mechanical engineering usually undergoes a process with a sequence of activities including identification and definition of requirements, conceptual design to create various ideas and solution candidates, embodiment design to determine major configuration and parameter values, and detailed design to achieve geometric descriptions including dimensions and tolerances. Despite that CAD theory has been well developed [5] and CAD systems have been widely used in mechanical engineering design, commercial CAD systems are primarily used in detailed design stage to model design solutions in the form of design geometry and to evaluate the design solutions through simulations such as finite element analysis (FEA) and computational fluid dynamics (CFD). Since design is considered a creative activity to achieve a design solution from design requirements, intelligent CAD systems are expected to support early design stages, including conceptual design and embodiment design.

With the advances of information technologies, particularly artificial intelligence and machine learning, research on intelligent CAD has been carried out in the past decades [2]. Results achieved in design theory and methodology have also been employed in the development of intelligent CAD systems. Despite the progress, conceptual design and embodiment design functions have not been supported in the present commercial CAD systems.

The research summarized in this paper provides an approach for developing future intelligent CAD systems to support conceptual design and embodiment design, in addition to the traditional detailed design based on geometric modeling. In this approach, the CAD system is used for detailed design, while AND-OR trees and optimization are used for conceptual design and embodiment design. The geometric descriptions in detailed design and the non-geometric descriptions in conceptual design and embodiment design are integrated through CAD API (Application Programming Interface).

Framework of the Intelligent CAD System:

Fig. 1 shows the framework of the intelligent CAD system. Design activities in the intelligent CAD system are modeled in the sequence of requirement definition, conceptual design, embodiment design, and detailed design.

- *Requirement Definition*
  Design requirements are defined by an AND-OR tree with nodes to model design functions and sub-functions. A design function node is associated with parameters. In addition, qualitative constraints and quantitative constraints can also be defined in design requirements.
- *Conceptual Design*
  The bottom design function nodes in the AND-OR tree are then associated with possible partial solutions, including components and assemblies. From this generic AND-OR tree, different conceptual design candidates with different components and assemblies are created through tree-based search. From all the candidates, the best one is selected as the final solution.

- *Embodiment Design*
  An embodiment design solution is evolved from a conceptual design solution to determine its structure of configuration and values of parameters. A configuration is defined by a collection of components and assemblies, and relations among components and assemblies. Components and assemblies in a configuration are associated with their parameters. Optimization can be used to identify the optimal values of variable parameters in a configuration and the optimal configuration.
- *Detailed Design*
  A detailed design is modeled by its geometry with a CAD system. Dimensions and tolerances are also modeled in the detailed design. A detailed design model is created from its embodiment design model, in which geometric shapes of the components and positions/orientations of the components/assemblies are modeled by parameters.

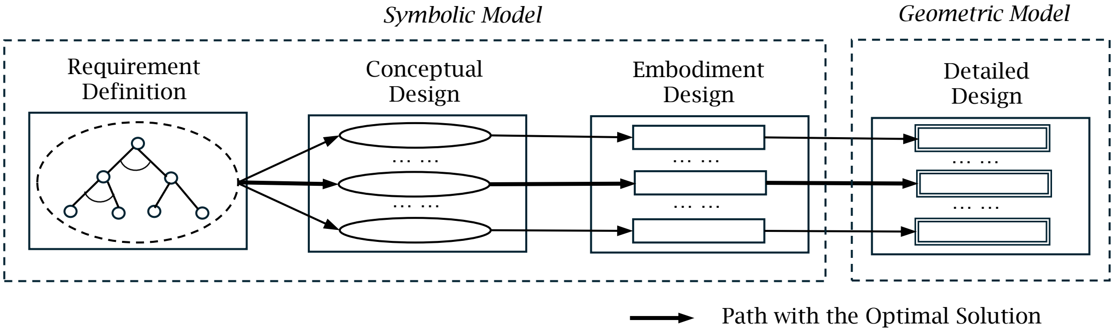
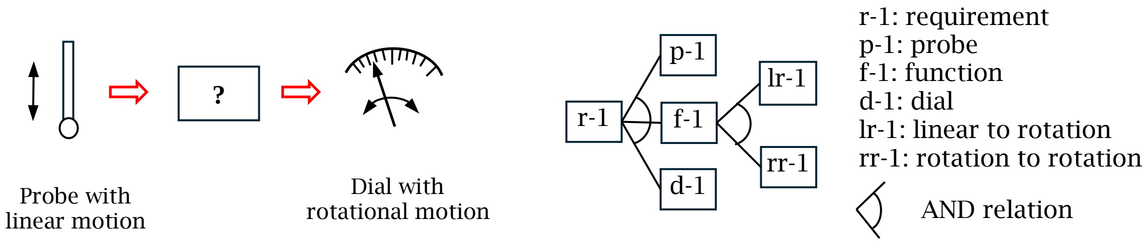


Fig. 1: Framework of the intelligent CAD system.

As shown in Fig. 1, various design solution descriptions in different design stages are classified into two categories: the symbolic model with descriptions in conceptual design and embodiment design, and the geometric model with descriptions in detailed design. The geometric model is defined by a CAD system (e.g., SolidWorks). The symbolic model is defined by an add-in module of the CAD system implemented using the CAD API (e.g., SolidWorks API).

Modeling of Design Activities in the Intelligent CAD System:
Design activities in the intelligent CAD system are modeled by requirement definition, conceptual design, embodiment design, and detailed design.

Requirement Definition
Design requirements are usually first obtained as customer needs and then converted to engineering specifications. Fig. 2(a) shows an example with the requirements to design a mechanism to transform a linear motion of the probe into rotational motion of the dial to display the measure.



(a): Design requirements. (b): Modeling of design requirements.

Fig. 2: Requirement definition.

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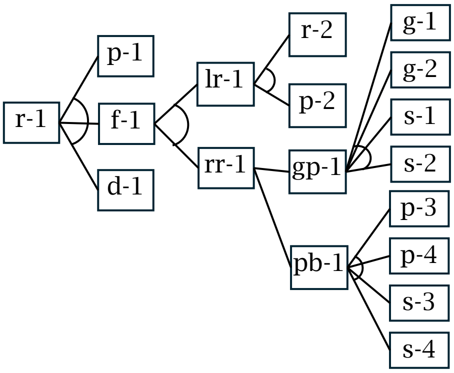
Design requirements are modeled by an AND-OR tree [1,3] as shown in Fig. 2(b). A node in the AND-OR tree can be either a function (e.g., the *lr-1* for linear-to-rotation transformation) or a design condition given before the design process (e.g., the *p-1* for the given probe). When all sub-nodes are used to support a super-node, these sub-nodes are associated with an AND relation. When only one of the alternative sub-nodes is used to support a super-node, these sub-nodes are associated with an OR relation. A node can be defined by its parameters (e.g., ratio of the rotation-to-rotation transformation *rr-1*). Constraints (e.g., the ratio of *rr-1* should be larger than 1.5) can also be defined in the requirements.

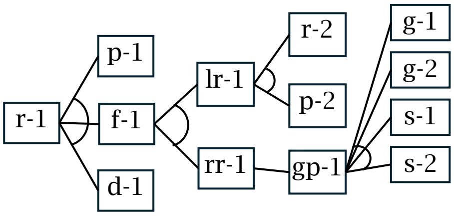
In the example shown in Fig. 2, the motion transformation function *f-1* is achieved by two sub-functions, *lr-1* and *rr-1*, associated with an AND relation. The function *lr-1* is to convert a linear motion to a rotational motion, and the function *rr-1* is to convert a small rotational motion to a large rotational motion.

Conceptual Design

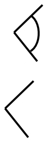
The first step in conceptual design is to extend the design requirement AND-OR tree by creating possible partial solutions to the function nodes at the bottom of the AND-OR tree, as shown in Fig. 3(a). In this example, the linear-to-rotation transformation function *lr-1* is achieved by a rack-pinion mechanism with a rack *r-2* and a pinion (i.e., small gear) *p-2*. The rotation-to-rotation transformation function *rr-1* is achieved by two different solutions: a gear-pair mechanism *gp-1* and a pulley-belt mechanism *pb-1*. These mechanisms are further defined by gears, pulleys, and shafts. In the AND-OR tree, a partial design solution is defined by a component (e.g., *g-1* for a gear) or an assembly (e.g., *gp-1* for a gear-pair). The sub-nodes of a super-node are associated with either an AND relation or an OR relation. The bottom nodes of the AND-OR tree are defined by components.



(a): The generic AND-OR tree.



(b): A created conceptual design solution.



r-1: requirement, p-1: probe, f-1: function, d-1: dial, lr-1: linear to rotation, rr-1: rotation to rotation, r-2: rack, p-2: pinion, gp-1: gear-pair, g-1: gear, g-2: gear, s-1: shaft, s-2: shaft, pb-1: pulley-belt, p-3: pulley, p-4: pulley, s-3: shaft, s-4: shaft

Fig. 3: Conceptual design.

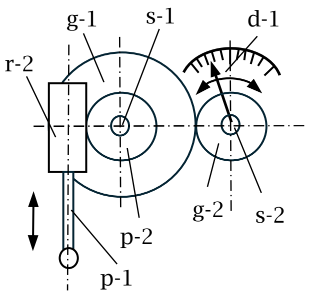
From the generic AND-OR tree, different conceptual design candidates can be created through tree-based search. The following rules are used to create a conceptual design candidate [1,3].

- The root node of the AND-OR tree should be selected first.
- When a node is selected and its sub-nodes are associated with an AND relation, all these sub-nodes should be selected.
- When a node is selected and its sub-nodes are associated with an OR relation, only one of these sub-nodes should be selected.

Fig. 3(b) shows a conceptual design candidate created from the generic AND-OR tree given in Fig. 3(a) through tree-based search. A conceptual design candidate is modeled by a tree with only AND relations.

Embodiment Design

The structure of the configuration and values of parameters are determined in the embodiment design stage, as shown in Fig. 4. A configuration is defined by an AND tree with a collection of nodes in the AND tree. In the AND tree, the bottom nodes are component nodes, while the other nodes are assembly nodes. A component or an assembly node is defined by parameters (e.g., module *m*, tooth number *z,* and diameter *d* of the gear *g-1* in Fig. 4). A parameter is assigned a specific value (e.g., the tooth number *z* of the gear *g-1* is assigned as 60).



(a): Embodiment design solution.

Configuration:

r-1: requirement, p-1: probe, f-1: function, d-1: dial, lr-1: linear to rotation, rr-1: rotation to rotation, r-2: rack, p-2: pinion, gp-1: gear-pair, g-1: gear, g-2: gear, s-1: shaft, s-2: shaft

Parameters:

r-2 (rack): l = 80 mm, w = 20 mm, t = 10 mm
p-2 (pinion): d = 60 mm, t = 10 mm, m = 2 mm, z = 30
g-1 (gear): d = 120 mm, t = 10 mm, m = 2 mm, z = 60
g-2 (gear): d = 60 mm, t = 10 mm, m = 2 mm, z = 30
s-1 (shaft): d = 10 mm, l = 60 mm
s-2 (shaft): d = 10 mm, l = 30 mm

(b): Configuration and parameters of the embodiment design solution.

l: length, w: width, t: thickness, d: diameter, m: module, z: tooth number

Fig. 4: Embodiment design.

When parameters are design variables, numerical optimization can be used to achieve the optimal values of these variable parameters. Suppose the i-th design configuration C_i is defined by its variable parameters $\boldsymbol{X_i}$, the optimal values of $\boldsymbol{X_i}$ are achieved by:

$$\min_{w.r.t.\boldsymbol{X_i}} F(\boldsymbol{X_i}) \tag{3.1}$$

where $F(\boldsymbol{X_i})$ is the optimization objective function (e.g., cost) to be minimized. Constraints can also be considered in parameter optimization. Among all the configurations with the optimal parameter values, configuration optimization [1] is carried out to obtain the optimal design configuration.

$$\max_{w.r.t.C_i} F(\boldsymbol{X_i^*}) \tag{3.2}$$

where $F(\boldsymbol{X_i^*})$ is the optimal objective function value corresponding to the optimal parameter values $\boldsymbol{X_i^*}$ for the i-th configuration C_i.

Detailed Design

A detailed design is defined by the geometric model of a CAD system, as shown in Fig. 5. The geometric model is created from the symbolic model of a configuration. For each component node in the configuration tree, its geometry is defined by the geometric primitive using the parameters of the component. For example, geometries of the rack *r-2* and the pinion *p-2* are defined by a block and a cylinder as shown in Fig. 5(a). A primitive can also be defined by extrusion or revolution of a 2-D sketch. Primitives can be moved and rotated to new positions. A primitive can also be added to or cut from another primitive to form a complex geometry.

For each component or assembly, its position is defined by 6 parameters: 3 location parameters *dx*, *dy* and *dz* representing translations in X, Y and Z directions, and 3 orientation parameters *rx*, *ry* and *rz* representing rotations about its X, Y and Z axes.

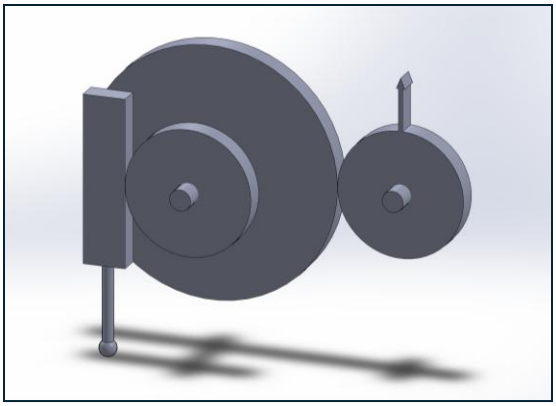
Conversion from the symbolic model in embodiment design to the solid model in the detailed design is conducted through CAD API (e.g., SolidWorks API) [4].

```
r-2: rack
  positions
    dx=–50, dy=–40, dz=30, rx=0, ry=0, rz=0
  geometry
    block(w, l, t) = block(20, 80, 10)
```

```
p-2: pinion
  positions
    dx=0, dy=0, dz=30, rx=0, ry=0, rz=0
  geometry
    cylinder(d, t) = cylinder(60, 10)
```

… …

(a): Positions and dimensions of components.



(b): Solid model in a CAD system.

Fig. 5: Detailed design.

Conclusions:

While CAD systems without intelligence cannot support true design activities, intelligent systems without geometric modeling functions also face difficulty in mechanical engineering design. To reduce the gap between geometric modeling-based design and intelligent design, a framework to support design activities in conceptual design, embodiment design, and detailed design is presented in this paper. Characteristics of this approach are summarized as follows.

- Intelligent design plays a critical role in the design process to identify the design solution from the design requirements. In this work, AND-OR trees, tree-based search and optimization are employed to support the conceptual design and embodiment design activities in the intelligent CAD system.
- The geometric model is effective in detailed design to define the final design solution, evaluate the design solution through simulations, and create information for the subsequent life-cycle phases, such as manufacturing. In this work, the geometric shape descriptions and position descriptions stored in the component and assembly nodes of a configuration in embodiment design are converted to a solid model in the CAD system through CAD API.

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