Kinematic Synthesis with Configuration Spaces

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Abstract. This paper introduces a new approach to the conceptual design of mechanical systems from qualitative specifications of behavior. The power of the approach stems from the integration of techniques in qualitative physics and constraint programming. We illustrate the approach with an effective kinematic synthesis method that reasons with qualitative representations of configuration spaces using constraint programming.

Keywords. Conceptual design; Configuration; Constraint programming; Spaces & Qualitative physics

1. Introduction

The overall goal of our research is to derive computational theories of conceptual or pre-parametric design. As manufacturing technologies change, as new materials are developed, and as new design constraints emerge (e.g., designs with recyclable parts, and designs that assemble and disassemble easily), basic conceptual design procedures for electromechanical systems require effective use of computer tools in the early stages of design. Our specific aim is to use methods from qualitative physics and constraint programming to build new computational prototyping tools for conceptual design.

This paper presents a conceptual design system in the area of mechanism synthesis. Mechanisms are an important part of most electromechanical systems. Mechanisms transmit motion from one rigid body to another. An example is the mechanism in a quartz watch that uses the oscillating crystal to drive the minute hand at twelve times the rotational speed of the hour hand. Another is a rack-and-pinion steering of an automobile that converts rotation about one axis (the steering action) to two different rotations (the turning of the front wheels). Our design system takes as input constraints on the motion of a mechanism in qualitative mathematical form. As output, it produces a systematic enumeration of mechanism topologies and geometries that satisfy the given constraints. It also performs high-level simulations to demonstrate the feasibility of the design. The conceptual designs produced by our system can be refined and optimized by specialized expert systems using additional constraints on cost, material, manufacturing and assembly.

We illustrate our design system with a simple example. Consider the synthesis of a windshield wiper which is powered by a shaft rapidly rotating around the z axis and whose output is a low-frequency oscillation in the yz plane. Note that this is only a partial description of the input and output motions of this device. We describe this incomplete specification as a set of constraints in our predicate motion vocabulary.

Input motion: rotation ((0, 0, 0), (0, 0, 1)), speed (20).
Output motion: rotation ((0, Y, Z), (1, 0, 0)), frequency (F), range (R),
0.5 < F < 2, π/2 < R < π.

Rotations are specified by their centers and directions of axes: rotation (center, axis). The capital letters Y, Z, F, R denote variables, whose values will be instantiated during design. The specification imposes no restrictions on the placement of the output oscillation of the wiper (the variables Y and Z are unconstrained), while its frequency and range are constrained to be within given intervals. As we shall see later in the paper, our motion predicates are a shorthand notation for describing sets of configuration spaces.

The first structure enumerated by the system is

1 This design solves the problem with \( F = 0.8333, Y = 2, Z = -6 \).
shown in Fig. 1. It employs a worm-spur pair which converts the uniform input rotation around the z axis to one about the x axis. The spur gear drives a crank rocker and the wiper output is tapped from the rocker. Our system calculates the position and orientations of the gears and the crank rocker. Note that both the topology and the types of kinematic pairs of the mechanism are determined, together with their actual dimensions. Our design is physically implemented in Technics\textsuperscript{TM} Lego. Another design, shown in Fig. 2, that satisfies the same motion specifications, realizes the oscillatory output motion using a rack-and-gear pair, where the rack is driven by a slider crank. The crank is rotated uniformly by a worm-spur pair, where the worm is driven by the motor. This design is also found in [21].

There are two unique aspects of our method. First, our synthesis algorithms are grounded in a mathematical theory of motion composition that is based on configuration spaces. We compile the detailed theory of motion synthesis into a qualitative form that preserves essential distinctions for specifying and solving an interesting class of kinematic synthesis problems. We introduce a property called 5,0-preservation (join-preservation), which is a constraint on qualitative motion languages that is needed to guarantee the generation of correct designs. Second, our algorithms simultaneously take into account a variety of constraints during the synthesis process. In the wiper example, motion constraints and dimensional constraints are handled simultaneously.

Relevant constraints are enforced as soon as they become applicable. This is what makes the generation process efficient: we elaborate on this point in Section 6. The two windshield wiper designs were generated and rendered in about a second each on a Sparcstation 1+. Our synthesis algorithms are fully implemented, and all the examples presented in this paper are designed by our system. Our system enumerates designs ordered by increasing\(^2\) complexity. It has produced innovative designs for a number of common devices described in [21] including electric mixers and clocks.

1.1. The Problem: Motion Synthesis

Kinematic synthesis is the problem of determining a three-dimensional structure of rigid parts that implements a given motion specification. Kinematics only considers motions and not the forces that cause the motions. The solution to the kinematic synthesis problem is structured in two phases: type and number synthesis and dimensional synthesis [20]. In type and number synthesis, the topological arrangement of links and the nature of the kinematic connections between links are determined. The link lengths are derived during dimensional synthesis. Sophisticated numerical

\(^2\) We have a simple metric for complexity which counts the number of primitives in a design.