The Role of Abstraction in Plave Vocabularies

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The Role of Abstraction in Place Vocabularies

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ABSTRACT

Understanding mechanical behavior is an important part of both commonsense and expert reasoning which involves extensive spatial knowledge. A key problem in qualitative spatial reasoning is finding the right level of detail to support differing needs of reasoning methods. For example, analysis of failures may involve describing every surface imperfection; but, to gain an initial understanding of device behavior, one needs to eliminate extraneous information.

People seem very good at varying their level of resolution to meet the needs of the activity being described, but in machine understanding this has proven to be a dilemma. In order to understand an artifact one needs to impose some level of abstraction, yet to obtain a sufficient level of abstraction, without omitting critical details, one needs to understand the artifact. Our solution simplifies descriptions of mechanical devices using quantitative information about qualitatively significant regions. Configuration space representation of the kinematic pairs of a mechanism serves as the underlying metric diagram to answer questions concerning contact between the components and provide the foundation for construction of a purely symbolic device description, the place vocabulary. We explore the effect of abstracting the configuration space on condensation of the place vocabulary, showing how it makes qualitative reasoning about complex mechanisms, such as the mechanical clock, tractable. Examples shown are based on an implementation.

INTRODUCTION

The goal of qualitative mechanics is to produce a symbolic theory of analysis for complex, rigid body devices. We base this theory on first principles to allow explanations of the behavior both of common mechanisms such as gear trains, pistons, and ratchets, as well as of mechanisms which contain unusual devices such as mutilated gears and clock escapements. These explanations may be used to predict the behavior of an unknown mechanism, determine the suitability of a given device for a task, diagnose mechanical failures, and critically analyze new mechanisms.

The context of this work is a generative model of mechanical analysis which determines behavior from a geometric description of the components and a dynamic description of external forces affecting the mechanism. Specifically, we take drawings of rigid objects, determine how they will interact, partition these interactions into equivalent behaviors, combine these behaviors for all components

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in the mechanism, propagate external forces acting on the system, and produce an envisionment showing possible changes in motion and position throughout the mechanism (Nielsen, 1988).

This paper focuses on the qualitative and geometric knowledge required when partitioning equivalent behaviors. We investigate ways to reduce combinatorial explosion when combining the pairwise interactions of components throughout an entire mechanism.

OVERVIEW

This paper begins with a brief history of work done in qualitative kinematics and the ideas necessary to understand this work. The examples provide an introduction to the type of reasoning qualitative mechanics can accomplish. The section "Building the place vocabulary" discusses our theory of place distinction. Following that we discuss the abstraction of these distinctions in order to allow analysis of larger mechanisms which is the core of this work. Finally we discuss future work and conclusions.

BACKGROUND

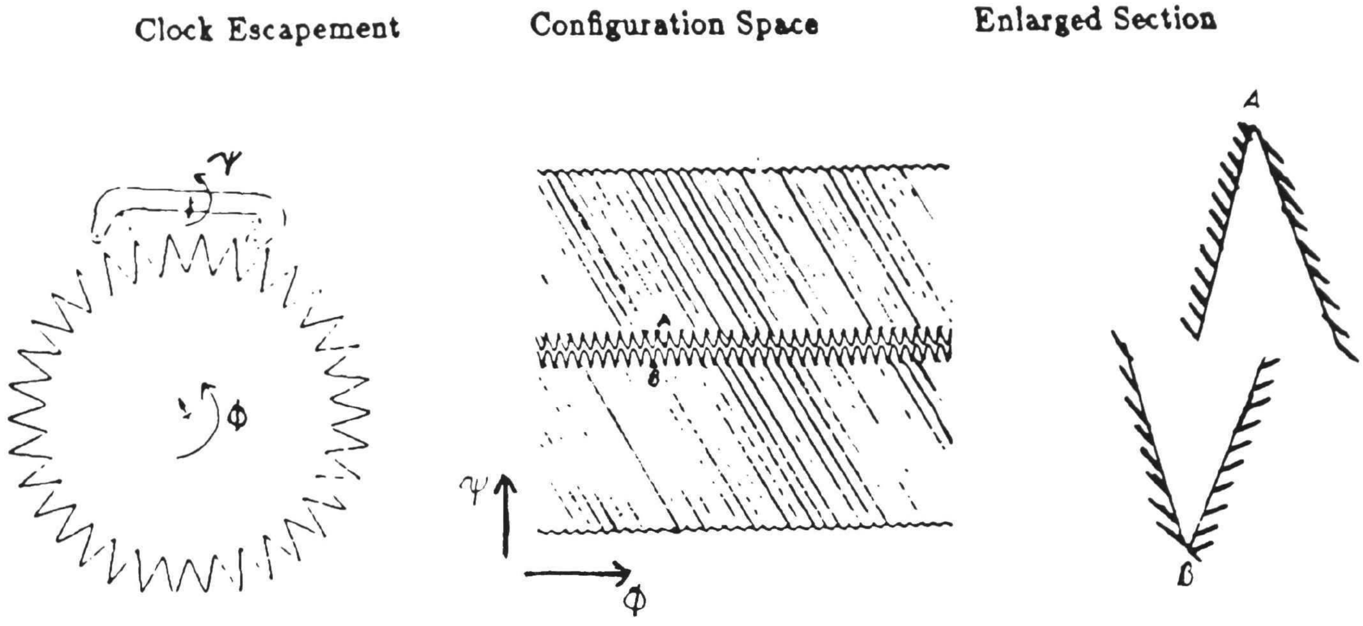
When inspecting a power train, observing gears gives one some general expectations of their behavior; however, explaining why gears bind requires a focus on the individual parts and more sophisticated observations of their interactions. A purely qualitative description would not benefit from additional observation, but by allowing new metric information to modify our symbolic representation we can construct a new qualitative description which depicts the conditions for the gear to jam. Conversely, if we considered every possible way the gears could jam and bind, we would be overwhelmed and never understand the overall mechanism.

Much of the previous research in symbolic approaches to kinematics (Davis, 1986; de Kleer, 1975; Laughton, 1985; Pu & Badler, 1988; Stanfill, 1985) relied on shape recognition or a priori knowledge of kinematic pairs (the parts of the mechanism which may come into contact). This knowledge would require an enormously large part library, restrict analysis of new designs, and allow only one level of analysis.

One way to simplify analysis of mechanisms is to abstract the shapes of the original components. For example, Gelsey (Gelsey, 1987; 1988) represents gears without teeth. The problem with those approaches is they presuppose the importance of surface features to the device's behavior. Such presupposition cannot be done in general. Removing the teeth from a scape wheel (figure 1A) makes analysis of its behavior impossible.

Order of magnitude reasoning methods (Raiman, 1986; Mavrovouniotis & Stephanopolous, 1987) have proven elusive in the analysis of mechanical devices because the size of a component has no relation to its relative significance. A surface with a small hole would have negligible effect on the motion of most objects across its surface, but in conjunction with an object which has an appropriately sized, spring loaded pin these components create a fundamentally significant behavior, latching.

Faltings, 1987a, demonstrated (based on the results of Reuleaux, 1876) the limitation of reasoning about shape information independently and indicated the need for analysis to proceed at the level of the kinematic pair. We show a generative approach to qualitative kinematics which uses information about the pairwise interactions of the components to determine the significance of a



Clock Escapement **Configuration Space** **Enlarged Section**

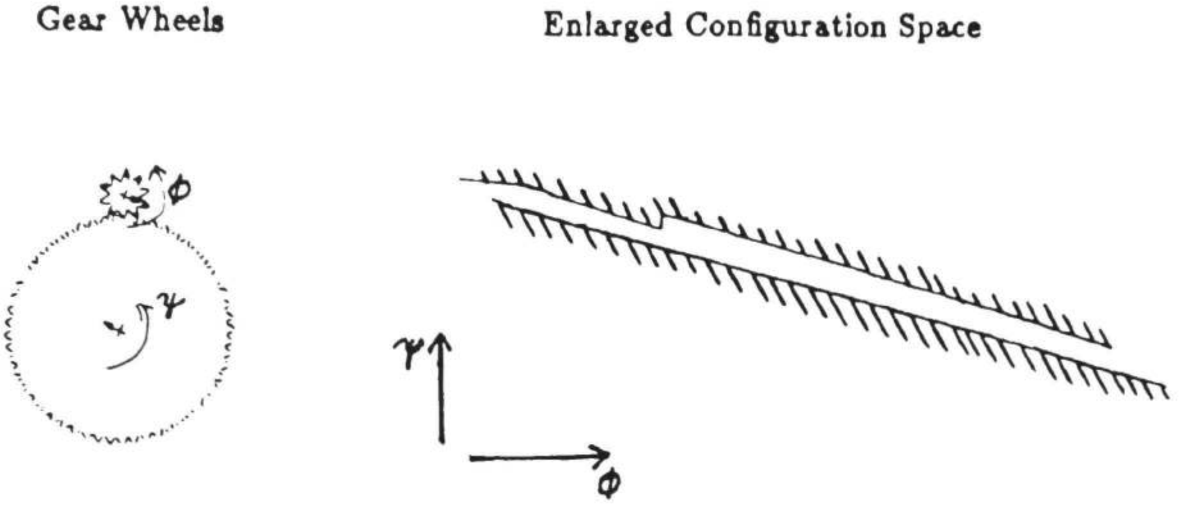
Figure 1: Clock escapement and corresponding configuration space

feature to mechanism behavior. This may be used to construct a library of common mechanisms, to enable reasoning about unforeseen variations, and to facilitate reasoning at varying levels of detail.

BUILDING THE PLACE VOCABULARY

Our initial kinematic analysis consists of a transformation of the kinematic pairs into their *configuration space* (introduced in Lozano-Perez & Wesley, 1979 and developed for mechanisms by Faltings, 1987b). A configuration space is the result of plotting overlapping (blocked) and non-overlapping (free) configurations for each allowable motion of each object. Unconstrained objects have six degrees of freedom, three translational and three rotational motions, and so a configuration space for two unconstrained objects would require six dimensions to describe every combination of positioning. However, components of mechanisms, by definition, are relatively constrained, and "single degree of freedom mechanisms are the forms used most frequently (Erdman & Sandor, 1984)," so each kinematic pair needs only a two dimensional representation to describe all possible interaction.

Figures 1 and 2 show some kinematic pairs and their configuration space representations. Lines parallel to the axes represent a pure rotation of a single object counterclockwise from 0 to 2π. Shaded regions indicate blocked configurations where the objects would overlap, and unshaded regions represent free configurations where the two objects do not touch. The curves between the free and blocked regions represent configurations where the objects are in contact.



Gear Wheels

Enlarged Configuration Space

Figure 2: Gear wheels and corresponding configuration space

Because a complete spatial analysis of each point would take infinitely long, the space of consideration must be partitioned; but an unintelligent approach to place abstraction will either require a huge number of cells or lose relevant information. Our approach uses the concept of a place vocabulary[1] (introduced in Forbus, 1981). A *place* is a connected region of space in which all points share relevant properties, and a *place vocabulary* is the set of all places covering the space of interest. The metric diagram allows us to determine which places are adjacent and predict the configuration which results when one or more objects move.

For example, as long as one is walking along a wall the expectation is that it will not impede your progress, but upon reaching a corner the direction of travel must cease or change. Despite the size of the wall it may be represented with a single place, and even though the corner is a very small region, it is represented as a distinct place. In mechanism the shape of the surfaces of the objects in contact affect their possible behaviors, and the next possible contacts define the behavioral predictions of objects. So our place vocabulary will consist of regions where the contact is equivalent (in some sense) and non-contact (free) regions which are divided according to the next contact they can transition to.

We group places in the place vocabulary according to four types distinguished by allowable motion and contact. These are constraint segments, joins, free space divisions, and full faces. The properties of each type are discussed below.

Constraint segments (CSEGs) form the boundaries between free and blocked regions in configuration space. They represent arrangements where the objects make contact. A CSEGS prevents

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[1] Joskowicz (Joskowicz & Addanki, 1988) uses a similar concept, but refers to it as a *region diagram*.

motion into the open half plane centered on its reverse surface normal.

Joins are the points where surfaces meet. In previous work in qualitative kinematics the analysis of points was largely overlooked. (The exception being Shoham, 1985, which treats only points.) Analysis at a point is only slightly more complex than along a smooth constant curve, but including points in the analysis roughly doubles the size of the place vocabulary.

Joins will have qualitatively different behaviors depending on whether the adjacent surfaces are concave or convex. We call a join an *concave* if the surface normal of the segment on one side of the join lies in the same open half plane as the surface normal of the segment on the opposite side; and *convex* otherwise. The motions prevented by an concave join are the union of the set of motions prevented by each of the adjacent segments, while the motions prevented by a convex join are the intersection of the set of motions prevented by each of the adjacent segments.

Some interesting kinematic pairs, such as clock escapements, do not stay in contact and may produce intermittent motions. Even more common kinematic pairs need to have some play between the parts to reduce friction. Free space divisions (FSDs) partition regions of open space to provide behavioral distinctions when the objects are not in contact.

The number and form of the FSDs affect the complexity of the resultant place vocabulary. The minimum FSDs should distinguish where the shape of the contact changes, since this corresponds to a qualitative change in the behavior of the mechanism, and should divide the open region according to the allowable motions of each individual object. Since each object only has one allowable motion, these divisions are lines.

The open areas of space bounded by CSEGs, FSDs, and joins are called *full faces*. They impose no restrictions on the motion of the object, but by adjacency they answer they question, "If this motion continues, what will happen next?"

One way to characterize the configuration of an entire mechanism would be to calculate the configuration space resulting from each possible motion of each of the components. Yet, even if each component only contributed one degree of freedom, and hence one dimension to this space, even simple mechanisms would produce enormously complex spaces. Further mechanical engineers do not seem to think of the entire mechanism at once as this method would suggest. Instead we use a vector, consisting of one place from each place vocabulary of each kinematic pair, to characterize all possible configurations of the overall mechanism (the *place vector*). As we see in the next section, combining all possible locations of all parts still results in an enormous number of possible place vectors. The solution is to ignore some of these combinations without loosing sight of "significant" behaviors.

ABSTRACTING THE PLACE VOCABULARY

The full place vocabulary for the clock escapement given in figure 1 consists of over 1300 places. This by itself is not an unwieldy number of distinct locations to consider in constructing a detailed analysis of this pair. But combining that information with 6000 to 60,000 places for each gear pair makes analysis of an entire clock become intractable before motion analysis is even considered. Information about periodically recurring patterns[2] reduces the number of places to 96 for the escapement and 16 for a typical gear. But since our clock has 6 gear pairs, its entire place vocabulary after this optimization would consist of about 1,600,000,000 places.

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[2] Faltings handles recurring surface patterns by recording repetitive surfaces and performing the configuration space transformation only once for all of these surfaces. (Faltings, 1987b for details.)

To produce a detailed analysis we would like to preserve information about how a qualitatively unique surface on the original part interacts with each surface on its opposite pair. For example, at one level of detail we may be interested in knowing what behavior the fore face of a gear tooth has on the top of the opposite gear tooth. But when reasoning about long kinematic chains we cannot possibly keep track of where each surface comes into play. At the most detailed level CSEG's may be distinguished by a labeling of the object's surfaces which gave rise to them. Alternatively, the most abstract distinction of CSEG's is by the orientation of their surface normals because this orientation restricts the possible motions of the objects and determines the direction of forces transmitted by contact. Adjacent CSEG's with qualitatively equivalent surface normals may be represented by a single place in the place vocabulary.

This abstraction collapses all adjacent surfaces with qualitatively equivalent surface normals into one functionally equivalent surface which reduces the number of places on a gear to 12 and on the escapement to 80 and reduces the overall place vocabulary to about 240,000,000 places.

By reducing the resolution (enlarging the grain size) of the configuration space, interactions between small irregularities on surfaces may be ignored. For example, the gear depicted in Figure 2 has certain interactions between the surfaces which prevent it from turning in the "up left" direction for a small interval. If this interval is below some ϵ it may be ignored at the risk of loss of accuracy. Doing this reduces the number of places on a gear to 3 and the number of places on the escapement to 50. The total number of places is now 36,450.

When resolution is reduced, the gap between parts also becomes less apparent. If the gap size between two parts is less than some ϵ a new place is created which is bounded on two sides. Conceptually this approach eliminates the play between the two parts and collapses three distinct places into one. Only free space may be eliminated this way and not blocked space since that would alter the mechanisms behavior. It is important that any reduction in the number of places collapses many adjacent regions into one rather than eliminating a region since doing otherwise may eliminate a previously possible transition.

These abstractions allow us, when considering gear behaviors, to reduce the number of places to one. (The escapement remains 50, which is the total size of our place vocabulary.) The practical effect of this is that arbitrarily long gear chains contribute no more to the complexity of the mechanism than does a single gear pair. This corresponds to the intuitive notion of a gear as producing a single constant behavior and validates other qualitative analysis rules such as "A and B form a parallel gear pair if their only possible motion are two coordinated rotations(Joskowicz, 1987)." However, our result was obtained from a first principles, geometric analysis. No "knowledge engineering" for specific parts or chains of parts was required.

CONCLUSIONS

We have demonstrated a method of abstracting geometric information to reduce the complexity of symbolic information in mechanism analysis. The advantages of this approach include the ability to construct an analysis of entire mechanisms, rather than of components. While previously the combinatorics of the problem have been prohibitive, we have produced a complete envisionment of a mechanical clock using a total of 234 qualitative states accounting for variations in motion and position.

A more detailed analysis of a mechanism might look at the way a subcomponent participates in the overall behavior of the mechanism, then look at a more detailed analysis of that subcomponent to provide further insight into the behavior of the mechanism. For example, the gear pair depicted will turn freely only in one direction. If we construct an approximate description of the gears turning freely, we should then reinvestigate the behavior of the gear in the overall mechanism to determine if it violates this unidirectional constraint.

In the future we would like to be able to perform analysis from courser sketches of mechanical components rather than from actual components. Slight irregularities could be removed by the simplification techniques discussed here, and barely occluded regions may provide clues to designer's intent. If a region is only slightly blocked, it may in fact have been intended as free.

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