Motion Economy and Planning

Özgen Canan
Turan Güneş Bul.
13. Cad. 1/1
Ankara, Turkey
ozgencanan@yahoo.com

Ayşenur Birtürk
Department of Computer Engineering
Middle East Technical University
İnönü Bul. 06531
Ankara, Turkey
birturk@ceng.metu.edu.tr

Abstract

We have formulated the motion economy problem as an AI planning problem. We have developed and formalized a model for representing the actions, environment and products of the domain. We have interpreted and represented the expertise of motion economy specialists as search control rules by using temporal formulas and used them to generate quality plans.

Introduction

Manual operations are an important component of many applications. Examples range from cooking, painting, and typing in daily life to assembling products in industrial plants. *Motion economy* deals with generating and improving plans for a certain group of simple tasks in industries where efficiency gain is achieved by reorganizing the actions in the plan. Given a desired configuration of the product and/or the arrangement of the workplace, a *motion economy specialist* tries to generate a plan, which is composed of fundamental hand motions and is economic from the viewpoint of motion economy expertise (Barnes 1958). The discipline of motion economy was originated by Frank B. Gilbreth and his wife Lillian M. Gilbreth (Gilbreth and Gilbreth 1917). Gilbreths defined micromotion study by analyzing manual operations and breaking them into primitive steps named *therbligs*. These steps cover all the possible operations done by the two hands as well as cognitive tasks such as "search" and "select". Barnes (Barnes 1958) improved on Gilbreths' work by analyzing the factors that contribute to more effective work and by adding two therbligs for holding an object and planning a job (Ferguson 2000).

The importance of motion economy lies in the fact that manual jobs can be performed more effectively if the cognitive and ergonomic limitations of humans are taken into account. For instance, Gilbreths observed that the hand was a poor vise and such use caused great fatigue. Thus, they suggested the use of a holding device while assembling certain parts. They also suggested that the length of the hand movement should be kept to a minimum to reduce fatigue.

In this work, we have formulated the motion economy problem as an AI planning problem where sequences of therbligs are generated. The most challenging aspect of our work has been to represent the therbligs and the motion economy principles in an existing planning framework. We have developed and formalized a model for representing the actions, the environment and the products of the domain. In general, representation of a product and definition of a goal determines the tasks to be done. We have also represented the workspace and the properties of the work environment.

We adapted the knowledge representation schemes used by assembly sequence planning studies to manual assembly plans. Operation plans are constructed from the detailed specifications of products. We have also benefited from assembly planning in the representation of the product configurations during the phases of planning where the product is partly established. To generate the operational plans, we used TLPLAN, a forward chaining planner with a search control mechanism based on domain specific knowledge (Bacchus 2001). We have used temporal logic to represent motion economy principles as search control rules. We picked TLPLAN because our problem requires the modeling of concurrent actions, durative actions, and resources (Bacchus and Ady 2001).

Our contributions are threefold. First, we apply AI techniques to manual operations. Traditionally, AI technology has been used in robotic assembly problems. Second, we represent sequences of manual operations as plans and use AI planning techniques to generate them. This is a novel application of AI planning. Third, we code effective search control rules from the field of motion economy and use them to generate quality plans. This is particularly important in concurrent domains such as manual operations where two hands can be used in parallel.

In the remainder of this paper, we first show how to represent the world of motion economy. We then explain how to formulate the planning problem and generate the plans.

Representation of the World Model

Knowledge representation for motion economy domain can be grouped into four subdivisions. These are representation of the product, representation of the workspace, representation of the current world and representation of actions.

Representation of the Product

We represent the products using an extension of relational graphs. Relational graphs contain connection features in addition to the graph of connections. Atomic parts of the assembly make up the nodes in the connection graph and there is an edge for every pair of parts that contact with each other. These edges are referred to as *contacts*. Figure 1 shows the contact graph of a ballpoint pen assembly. Atomic parts of a ballpoint assembly are body (Bo), button (Bu), head (H), ink tube (I) and cap (C).

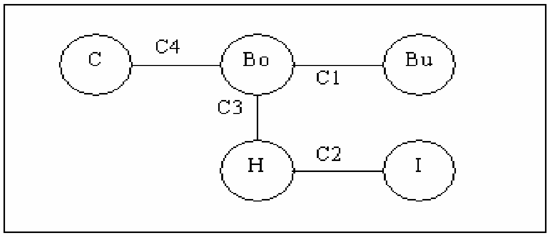

Figure 1: Contact graph of ballpoint pen assembly.

For each contact Ci, two sets of relations are formed (Bourjault 1984). The first set represents the contacts which become infeasible once Ci is established. This set is called the *cbein set*. For instance, body and head cannot be assembled if cap and body are assembled in ballpoint pen assembly. This precedence relation is represented by the predicate (cbein C3 C4). The other set contains the contacts that are required to establish Ci. This set is called the *cbei set*. We extend contact graphs to represent the use of tools. If a tool is listed in the attributes of a contact (the *ctool set*), the operator must use it while establishing the contact between the parts. Assembling two parts using a screwdriver is an example of such an operation. Another extension to the relational graph that we modeled is to use arcs from and to the same part to represent a transformation concerning a single part. We call these arcs *self-contacts*. A self-contact represents irreversible transformations of the part such as painting or drilling.

Formally, a relational graph is a pair <V, E> where V is a set of nodes that represent the atomic parts and E is a set of edges representing the contacts together with their cbein sets, cbei sets, and tools.

Representation of the Workspace

The *workspace* is the predefined area where all the materials used in the plan are stored and all the activities of the hand take place. Representation of the workspace is partly taken from the motion economy studies (Barnes 1958). We partition the workspace into nine discrete locations. One of them is called *working area*, where two-handed work can be done. Other locations are distinguished with respect to three properties, which are *side*, *distance* and *adjacent axis*. In practice, locations can be considered as lying on fuzzy regions for the two hands. These fuzzy regions can be defuzzified after the plan is generated.

Representation of the Current World

The representation of the world includes the location of the parts, tools, or hands; whether a part is correctly positioned; whether a part is being held by a hand; and whether a contact is established. The list of the predicates that represent these features as well as the "container" and "fixture" predicates are given in Table 1. Objects are stored in containers in the workplace. Fixtures are used to position objects.

Predicate	**Description**
(pos X)	Part X is positioned.
(at X L)	Location of X (part, hand or tool) is L.
(holds H X)	Hand H holds part X or tool X.
(established C)	Contact C is established
(container P L)	There is a container of P at L
(fixture P L)	There is a fixture of P at L

Table 1: Predicates representing the current world.

Representation of the Actions

We construct our operation plans with a subset of the *therbligs*, which correspond to the actions in our planning problem.

Transport_loaded is one of the therbligs, which we modeled and used during the process of generating the plans. *Transport_loaded* changes the location attributes of the hands and the objects it holds from their old locations to new locations. Below, the representation of this action is given as an example. The representation is similar to the ADL representation with the additional use of instant and delayed effects of TLPLAN. The instant effects represent the effects that take place as soon as the action is applied. The delayed effects happen after the action is over and enable the use of concurrent actions that can execute until the delayed effects take place.

```
Action (transport_loaded (h : hand, from : location, to : location)),
  PRECOND: ¬(busy h) ∧ ¬(empty h) ∧
           ¬(= from to) ∧ (at h from)
  INSTANT EFFECTS
    DELETE LIST: (at h from) ∧ ∀[x:(holds h x)] (at x from)
    ADD LIST: (will transport_loaded h to) ∧ (busy h) ∧
              (+= (tr-made h) 1) ∧ (+= (fatigue h) 1)
              ∧ (+= (rel-actions h) 1)
  DELAYED EFFECTS
    DELETE LIST: (will transport_loaded h to) ∧ (busy h)
    ADD LIST: (at h to) ∧ (init-action-counter h) ∧
              ∀[x:(holds h x)] (at x to)
```

The additional actions which we selected and modeled in this study are: t*ransport_ empty, select-grasp (search, select & grasp), release, assemble, disassemble, use (*as *disuse, use-with-fixture,* and *use-self-contact),* and *position.* The actions we did not represent (e.g., *unavoidable delay*) required the explicit representation of durations and were actions that did not contribute directly to the assembling process.

Generating Plans for Manual Operations

We use the forward chaining planning implemented in TLPAN to generate plans. Establishment of a contact is represented with a Boolean value. For the whole contact set, a true-false vector represents contacts already established (Homem de Mello and Sanderson 1990). An *assemble* or a *use* action makes one of these values true, while a *disassemble* or *disuse* action makes it false. Completing a product means having a certain subset of these values true (complete set in a conventional assembly sequencing problem). Locations of tools and parts are decided during plan generation. This is a part of the solution of the problems.

Search Control and Evaluation of the Plans

Search is controlled by modal checking of temporal formulas, relating to the states in the timeline starting from the current state (Bacchus and Ady 2001). We use first-order linear temporal logic where temporal formulas are obtained by adding temporal modalities to first-order formulas. We have developed three sets of search control rules: *common sense rules*, *goal-related rules,* and *motion economy rules*.

Common sense rules eliminate the exploration of illogical plans by pruning misleading states. Five common sense rules were devised in the course of this study and formulated as temporal formulas. One of these rules is "*do not consecutively establish and disestablish the same contact*". This rule prohibits the application of contact establishment actions on the same contact repeatedly unless another contact is subject to one of these actions in between.

Goal-related rules exploit the goal state information to prune search space and speed up the search. We have developed goal-related rules, which are robust to work with any kind of problems. One of these rules is "*do not grasp a part, if all of its contacts which are in the goal are infeasible*".

Motion economy rules represent the improvements that can be made to manual tasks. Gilbreths came up with these rules after watching workers, observing the common patterns and analyzing the changes that can be made. Applying these changes to a work sequence results in reduced total time, reduced fatigue, elimination of injury producing motions, and elimination of motions with high cognitive overhead (Ferguson 2000). Therefore, a plan that incorporates the motion economy rules is by default better than one that does not. The focus of our work was to incorporate motion economy rules into a planning framework by having them guide the choice of actions and sequences. In our implementation, we prepared a rule set after surveying a number of motion economy studies (Barnes 1958; Grandjean 1969; Karner and Bahya 1977; Mundel 1985; Niebel 1988). We selected twelve core principles, which can be expressed with the current representation of the world model.

1. Keep the work in the normal working area
2. Do not grasp anything from the normal working area
3. Grasp a single part instead of parts jumbled together
4. Provide a fixed place for the things worked with
5. Keep the parts that are used most frequently near the point of use
6. Keep transport as short as possible
7. Minimize the changes in the direction of motion
8. Eliminate abnormal motions
9. Move the arms simultaneously in opposite or symmetrical directions
10. Avoid keeping the arms extended
11. Eliminate the hand as a holding device
12. Distribute work evenly between hands

For instance, the sixth principle is represented by the temporal formula given below:

```
(always ∀[l:(isloc l)]  (= (dist l) max) ⇒
  (∃[h:(will transport_empty h l)] ∨
  ∃[h:(will transport_loaded h l)]) ⇒
        (¬∃[x:(isloc x)] ((= (dist x) normal) ∧
            (< (numconts x) (max-cont))) ∨
            ∃[h,p:(holds h p)] (goal (at p l)))))
```

Transportation usually cannot be eliminated from the plans. However, the time spent for transportation can be reduced by making shorter movements. There is a correspondence between the locations where objects are being grasped and the distance traveled by the hands. If there exists a location within the normal reach area, which has not filled its capacity for containers, transports to maximum reach area are not allowed. One exception is when a part is to be transported to its goal location.

Experimental Work

We have formulated and solved sample problems from the motion economy domain in our model. We chose representative problems to reflect the expressiveness of the representation scheme. In each problem, we examined the effects of the motion economy rules and observed that plan generation was faster and quality plans were produced. We worked with problems of varying complexity where the complexity of a problem depends on the number and type of parts, tools and contacts in a product specification. The problem complexity also increases with the number of feasible assembly sequences.

The depth-first search strategy was used for the experimental runs. The depth-first strategy was chosen over breadth-first search for three main reasons. First, we wanted to let the motion economy rules to guide the construction of a "good" plan rather than finding the shortest path solution using breadth first search. We were able to avoid the definition of a cost function by using the motion economy rules. Second, a state in our model consumes much more memory than ordinary planning problems as states keep track of temporal formulas as well. Breadth-first search uses more space than depth-first search since all the nodes at a level should be expanded before proceeding to the next level. Finally, we intended to maintain search control as a separate module by which we can experiment on sample problems.

The representative problems that we have represented and solved are

- *Ballpoint pen assembly*: an assembly problem.
- *Plates, nuts and bolts assembly*: a task in which the same type of parts are used more than once.
- *Producing a soldered cable*: a task which involves the use of tools and fixtures.
- *Brochure preparation*: a task in which a tool usage on a part changes the nature of the part.
- *Table preparation with a fast food meal kit*: a disassembly problem.

We observed the following behavior with all the domains we have listed: the plans were longer and took more time to generate when the motion economy rules were turned off. The best plans produced for these domains ranged from 15 to 21 parallel steps.

Conclusion

AI planning tools have not been used in the motion economy before, and no representation scheme for operation plans was present. It is the first time that the motion economy domain has been a subject of a knowledge engineering and AI planning study. In this study, we analyzed and represented the expertise of motion economy specialists as search control rules by using temporal formulas. In addition, a notion of common sense of manual operations was conceptualized. A set of common sense search control rules was devised and formulated to avoid plans that have unreasonable sequences of actions.

The effectiveness of the motion economy rules were shown by comparing the plans generated with and without the help of the rules. Justification of why a plan is evaluated as a good plan was given by describing the improvement the motion economy rules make as compared to the plans, which are obtained by applying only common sense search control. It was observed that motion economy offers a great deal of improvement to these raw plans.

Sample problems that we have formulated show the expressiveness of the representation scheme. A wide variety of tasks can be represented and solved by the planner. The plans generated satisfy the requirements of the task specifications well and they achieve this without representing a complex optimization problem.

Our model is generic and can be applied to any manual operation. We expect an increase in the system performance when our model is customized for a specific problem. Finally, some possible extensions to our implementation are to account for the preference of a hand for operations requiring force or precision, to represent hands as resources with variable capacity, to use a variable increase in fatigue, to represent actions with variable durations, and to add application-dependent goal-related rules.

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