Generating and Improving High-level Plans for Manual Operations

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Abstract. Motion study is one of the most crucial phases of planning production systems. It promises cost reduction in operation level, which affects the profitability of the whole system. For decades, operation analysis has been managed by common sense and expertise of the specialists. This study discusses applying AI planning tools for generating plans for operations, which are done with two hands. Improving the generated plans in terms of time and effort is also aimed with the use of AI techniques.

1. Introduction

Operations, which can be completed with the use of arms on a limited space, are defined as manual operations. They do not require traveling of the worker, use of the body parts other than arms and hands, like foot or trunk. In many industries, there are production sequences, which require simple manual operations. Although there is a trend to eliminate these kinds of jobs in a production system by having industrial manipulators do the job instead, manual operations continue to occupy a major part of working hours. They are widespread in the smaller industries. This study does not restrict manual operations to take place in production systems. We carry out manual operations constantly in our daily lives. Cooking tasks, typing and painting are just a few examples of these. All sorts of manual tasks are in the scope of this study.

Analysis of manual operations has been the research area of motion economy. Next section describes the general concepts of motion economy. Then the planning approach, which will be used in the study, is discussed. The paper will continue giving a more detailed model of the system. The following section discusses the application of motion economy to the plans.

2. Motion Economy

In the broadest view, manufacturing a new product is composed of three phases, which are planning, pre-production and production. Planning phase comprises the design of the product, the design of the processes, the design of the work method, the design of the tools and equipment, the design of the plant layout and determining the time standards. Pre-production is the phase of installing the new systems and testing them. Production phase is the continuous manufacturing activity of the designed systems. It involves controlling the system for quality assurance and improvement.

Motion and time study is a field of industrial engineering, which deals with the design and improvement of the operations in a production system. Motion study is related to designing a preferred method to achieve a task. Time study is related to timing of the operations and determining time standards. Motion study is also referred as methods study, work methods design, work study and work design. Work methods design deals both with the design of the processes and the design of the work method. The design of the processes is deciding the production operations and their sequences. This is a though job when a product has to visit many workstations and go through many operations till it finalizes. Whereas the design of the work method focuses on each of these operations one by one and aims to fit the operator to the job, rearranging the order of motions in the operation. Main approaches to be considered in finding the preferred method are eliminating all unnecessary work, combining operations or elements, changing the sequence of operations and simplifying the necessary operations. This analysis is the subject of this study and it will be referred as motion economy from now on.

Motion economy is a sub field of motion and time study. Frank B. Gilbreth and his wife Lillian M. Gilbreth originated motion study. Frank Gilbreth had an engineering background and Lillian Gilbreth was a psychologist. Gilbreth states that motion economy consists of dividing work into the most fundamental elements possible; studying these elements separately and in relation to one another; and from these studied elements, when timed, building methods of least waste. Gilbreth introduced micromotion study to analyze the operations by breaking them into primitive steps. Micromotion study consists of filming the operation, generating operation charts from the film and analyzing operations for improvement. However for most of the operations the analyst can derive a chart by observing the operator at work. No timing is needed to conduct motion study.

Most of the work is done with two hands and few fundamental motions are common in all of these tasks. Gilbreth came up with fundamental subdivisions of motion to describe all manual operations. He named these primitive actions as therbligs, which is Gilbreth spelled backwards. There are 17 therbligs, which are necessary to cover all the operations. The therbligs are given below. Their names are self-explanatory. The descriptions of the therbligs can be found in [1].

Search (Sh)	Select (Se)	Grasp (G)
Transport empty (TE)	Transport loaded (TL)	Hold (H)
Release load (RL)	Position (P)	Pre-position (PP)
Inspect (I)	Assemble (A)	Disassemble (DA)
Use (U)	Unavoidable delay (UD)	Avoidable delay (AD)
Plan (P)	Rest for overcoming fatigue (R)	

Besides cameras and stopwatches, which are used for filming and timing the operations, the only tool that guides the analysts in motion economy is the operation chart. Operation charts list the fundamental motions, therbligs, of the two hands, while they are performing a task, simultaneously. Operation chart is also called right hand-left hand chart. If the exact completion time of the therbligs is also included after conducting a micromotion study, the chart is called a simo chart, simultaneous-motion-cycle chart. A right hand-left hand chart for a simple operation is given in Figure 1. The task is to assemble two washers with a bolt, which are stored originally in a container. Left hand picks up bolt from the container and holds it. Right hand picks up a washer from the container and assembles it to the washer. Then it picks up the other type of washer and assembles it to the subassembly. Finally left hand carries the final assembly to a bin. Recall that same sequence of therbligs could define some other operation from any domain.

This planning and improvement process is usually the responsibility of industrial engineers and staff specialists. The aim in developing better methods is to reduce costs in terms of time, materials and energy. The number of primitive motions or amount of time required to complete a task can be a measure of improvement, as well as ergonomic concerns such as human fatigue and comfort. Human fatigue can occur in both physical and mental terms. Asymmetrical motions tire the muscles of the arms, while selecting continuously from alternatives challenges the brain. Humans cannot automate their hands as much as possible because of humans' coordination incapability of their two hands. Motion economy also considers this cognitive reality while generating plans that are realizable by humans.

The designs, represented by standard charts, guide the improvement process. There are standard methods for timing, observing and evaluating work. However the know-how, which is used in the methods design and improvement cycle, is organized as checklists or some rules of thumb. There are principles of motion economy related the use of human body, the arrangement of the work place and the design of tools and equipment. First three principles of motion economy related to the use of human body are as follows,

- The two hands should begin as well as complete their motions at the same time.
- The two hands should not be idle at the same time except during rest periods.
- Motions of the arms should be made in opposite and symmetrical directions and should be made simultaneously.

For each therblig, there are general considerations, which can be organized as checklists. Below are some of the questions arising with the use of the therblig select.

- Is the layout such as to eliminate searching for articles?
- Are parts and materials properly labeled?

– Can parts be pre-positioned during preceding operation?

<table>
<tr><th colspan="2">LEFT HAND</th><th colspan="2">RIGHT HAND</th></tr>
<tr><th>Therblig</th><th>Description</th><th>Therblig</th><th>Description</th></tr>
<tr><td>Transport empty</td><td>Reaches for bolt</td><td colspan="2" rowspan="3"></td></tr>
<tr><td>Select</td><td rowspan="2">Selects and grasps bolt</td></tr>
<tr><td>Grasp</td></tr>
<tr><td>Transport loaded</td><td>Carries bolt to working position</td><td>Transport empty</td><td>Reaches the container for first washer</td></tr>
<tr><td rowspan="2">Position</td><td rowspan="2">Positions bolt</td><td>Select</td><td rowspan="2">Selects and grasps the first washer</td></tr>
<tr><td>Grasp</td></tr>
<tr><td rowspan="9">Hold</td><td rowspan="9">Holds bolt</td><td>Transport loaded</td><td>Carries washer to bolt</td></tr>
<tr><td>Assemble</td><td rowspan="2">Assembles washer and releases</td></tr>
<tr><td>Release</td></tr>
<tr><td>Transport empty</td><td>Reaches the container for second washer</td></tr>
<tr><td>Select</td><td rowspan="2">Selects and grasps the washer</td></tr>
<tr><td>Grasp</td></tr>
<tr><td>Transport loaded</td><td>Carries washer to bolt</td></tr>
<tr><td>Assemble</td><td rowspan="2">Assembles washer and releases</td></tr>
<tr><td>Release</td></tr>
<tr><td>Transport loaded</td><td>Carries assembly to the bin</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>Release</td><td>Releases assembly to the bin</td></tr>
</table>

Fig. 1. Right hand left hand chart for the bolt and washer assembly task

The application of these principles is a though task for it requires too much attention and expertise from the analyst. The assembly operation shown in Figure1 is rather an inefficient way to do the task. In light of the general principles, we can conclude that the holding of the bolt must be eliminated by the use of a fixture, and selecting parts from the same container must be eliminated with the use of additional containers. This way the operation will be less tiring and quicker. When the operation is longer and there are many more therbligs in the design, the job of the analyst becomes harder. It will be much more difficult to capture the opportunities of improvement in the orderings of the therbligs.

3. AI Planning

The task of generating a sequence of actions to achieve a goal is called planning. Planners represent possible configurations of the world as states. A state is a conjunction of positive literals. States include positive conditions that are relevant to the planner. Any other conditions that are not mentioned are believed to be false. Most AI planners work on environments that are fully observable, discrete, finite and static. Functions are not allowed in representation of the states. Goal is a specific state of the world. It contains the conditions that are to be achieved. Actions are formed of two parts, which are preconditions and effects. Actions can activate when preconditions match with a state of the world. Activation of an action changes the state of the world by the introduction of new positive or negative literals. In other words an action affects the world by adding new literals to a state and deleting literals from a state. The sequence of actions, which transform the initial state to the goal state, is a plan.

State-space search is a straightforward approach for deriving plans. Both forward and backward state-space search can be used due to the two-sided structure of actions. Forward state-space search, which is also called progression planning, starts with the initial state and generates successors of the states by applying applicable actions on them. The search continues until the goal state is generated. In the absence of functions, any graph search algorithm that is complete may be used in the search. Forward search algorithms are inefficient since the state space of most planning problems are huge and there are many misleading actions. Finding a good heuristic to guide the search is very important. In backward state-space search, actions' effects are matched to at least one of the conjuncts of the goal or a sub-goal. Predecessors are generated by adding the action's preconditions to the state and by applying effects in reverse. Backward state-space search is sometimes called regression planning. Regression planning is more efficient than progression as it discards irrelevant actions in the search.

Partial-order planning

Both forward and backward search does not let the planner to focus on different subproblems separately, but they explore strict linear sequences of actions. A partial-order planner can work on different sequences of actions separately, delaying the choice of which comes first. This general strategy of delaying the choices is called the least commitment strategy. Partial-order planning allows for simultaneous actions in the resulting plans. Simultaneous actions can then be linearized in any possible way.

A partial-order planner searches the space of plans. The search starts with an empty plan, continues with adding steps into the plan until the goal is achieved. States of the search will mostly be unfinished plans. These plans have four components.

- A set of **actions** that make up the plan. The initial plan is composed of dummy *start* and *finish* actions. *Finish* has the literals of the goal as its preconditions and no effects, and *start* has no preconditions and has the literals of the initial state as its effects.
- A set of **ordering constraints**. These constitute precedence relationships between the actions. The constraints are in the form "A before B", for actions A and B. They do not impose immediate precedence.
- A set of **causal links**. A causal ink between two actions states that a precondition of an action is an effect of another. It is read as "A achieves p for B", where A and B are actions and p is a precondition of B asserted by action A. Causal links prevent other actions to undo p, during the interval between the end of action A and the start of action B.
- A set of **open preconditions**. The planner tries to satisfy all open preconditions during the course of the algorithm. Recall that the algorithm starts with open preconditions, which make up the goal.

A consistent plan has no cycles in the ordering constraints and no conflicts with the causal links. If a consistent plan can empty the set of open preconditions, it is a solution. The formulation of the partial-order planning algorithm is as follows.

- The initial plan, initial state, is formed with *start* and *finish* actions. An ordering constraint, "*start* before *finish*" is added. The set of open preconditions is the preconditions of *finish*, which are the conjuncts of the goal.
- The algorithm selects an open precondition arbitrarily and generates successors for every possible consistent way of achieving it. A causal link, regarding the open precondition and the action that achieves it, is added. The necessary ordering constraints are added to the plan. Any conflict between the new causal link and an existing action is resolved by carrying the existing action outside the protection interval created by the causal link. New successor states are added by replacing the action before or after the interval, if the plan remains consistent.
- If there are no open preconditions, the algorithm has reached the final plan. Since no inconsistent plans are generated during the algorithm, this check is sufficient.

It is important to use a good heuristic to guide the partial-order planning algorithm, because it is not always easy to decide how close the solution is. A straightforward heuristic is to use the number of open preconditions. One other method suggests selecting the open precondition that can be achieved with the least number of ways.

4. A Model for Hands and Therbligs

In [3], researchers introduce a process planning architecture, where the manufacturing system is represented over the devices, such as water pumps and valves, of the system, such as the objects in object oriented programming. Actions are defined as methods belonging to the devices, and they occupy the device as long as they are active. Partial-order planning is used to derive plans, allowing the devices to act simultaneously. This architecture replies to the needs of our system for several reasons. Let us first describe the model, the way it will be used for the methods planning for manual operations and then discuss the advantages of it.

The description of the general model with respect to [3] is as follows. Entities, which are the real performers of the actions in the system, are represented as agents. Actions are defined as methods belonging to the agents. An agent is occupied if an action, belonging to it, is active. Every agent has *a set of states E*, which describe the states in which the agent is, *a set of actions A*, all possible actions that are defined for the agent. Additionally every agent has *a name N*, which is unique for each agent, *a set of variables V*, which are needed to describe the actions of the agents, and *a set of codesignation constraints C*, which are the possible values that the variables can take. Conditions or the effects of the actions can include variables. Activation of the actions makes variables bind with the codesignation constraints, which are specific to the problem.

$$\text{Agent} = (N, E, V, C, A)$$

Actions of the agents have a unique name, a set of effects, which is defined by means of two lists, an addition list ADD, for the positive literals in the effect of an action, a deletion list DEL, for the negative literals that are introduced by the action. Actions also have a set of requirements, which is divided into three subsets, a list of previous requirements ANT, corresponding to the preconditions that are discussed so far, a list of simultaneous requirements DUR, which must hold while the action is active, a list of later requirements POST, that must be true after the action has finished.

$$\text{Action} = (\text{N, ADD, DEL, ANT, DUR, POST})$$

Every device in a manufacturing system is represented as agents, whereas the two hands carry out all the tasks in our system. Hands correspond to the devices in a manufacturing system and they will be represented as agents. Hence there will be an agent for the left hand and an agent for the right hand. States of the agents are determined by the therbligs that the hands are busy with. The set of actions for the hands is the whole set of therbligs. The set of variables for each hand are the objects that are manipulated by the actions. For the transport loaded therblig variables for the transported object, source and destination locations, for the assemble therblig variables for the two input parts and an output part must be defined. The set of constraints regarding these variables will be the parts available for use for the current operation, such as steel washer, rubber washer, bolt or screwdriver. The form of the agents, we have described so far, is intuitively given below, using a Lisp-like notation.

```
(Agent
   (N     Right_hand)
   (E     idle holding transporting …)
   (V     ?part ?assembly ?using ?location )
   (C     (?part steel_washer rubber_washer bolt)
          (?assembly assembly_wb assembly_wwb)
          (?using screwdriver brush)
          (?location bin container work_area))
   (A
      (ACTION  (N assemble)
      (ADD     (?assembly ?location))
```

```
        (DEL      (HOLD Right_hand ?part) (HOLD Left_hand ?part))
        (ANT      (HOLD Right_hand ?part) (HOLD Left_hand ?part))
                  (?part work_area) (?part work_area))
        (DUR      (HOLD Left_hand ?part))
        (POST     (HOLD Left_hand ?assembly)))
    (ACTION       (N Transport_loaded)
        (ADD      (?part ?location))
        (DEL      (?part ?location))
            …))
)
```

The domain of the problem will consist of the description of the agents and some axioms for the facts that are always true in the system. In addition, the initial state and the goal state will be represented by a conjunction of literals.

Partial-order planning algorithm will be used in generating plans. The partial-order planner supports simultaneous actions of the two hands. States of the agents and conditions of the actions will restrict the simultaneous usage of the same hand thanks to this architecture. Conditions of the actions, which must hold during and after the actions, are also a new concept to the traditional planners. Existence of two agents in the system will force the planner to employ whenever possible, since the partial-order planner is able to decompose problems and work on subgoals separately. These conditions also provide a way to apply motion economy principles to the plans. This will be discussed in the following section.

5. Applying Motion Economy to Plans

There are several considerations so as to improve the generated plans, in consideration of the principles and previous studies of motion economy. However as the planner is not implemented yet, only a discussion of possible approaches will be represented here. All approaches have their own pros and cons, but they all suffer from the nature of the accumulation of motion economy knowledge. As a field developed apart from programming aspect and relying on the expertise of the analyst, the knowledge is organized as checklists and principles. There is no low-level compilation of the know-how, which is designed to work on the sequence relations of the therbligs. Most work study books even find it hard to describe the methods governed by the improvement studies. Nevertheless this is one of the main motivations behind this study.

One approach would be reflecting the motion economy knowledge into the planning phase of the system. The planner can be guided by additional constraints inserted to the actions, while it chooses the agents to operate and actions to be applied. Especially, requirements of motion economy related solely on the use of some therbligs can be added to the constraints that must hold during or after the actions. For the select therblig, the container, from which the part is selected, may be constrained to include only that part rather than having more than one part. For the transport therbligs, reach area for the hand may be restricted. On the other hand this approach is not able to capture the possible modifications related to the sequence of the therbligs. Although these conditions may affect the simultaneous action of the other agent, there may be revisions that will change the order and type of many therbligs, which follow each other. The DUR and POST conditions can be used in designing the workplace during the generation of plans, suggesting for the type and place of the tools and containers.

A rule-based reasoner module can be built to work together with the planner. Rules can capture the inefficiencies concerning the order of the therbligs. The reasoner does not have to wait for the complete plans. As the partial-order planner searches in the space of unfinished plans, the rule-based reasoner can modify the unfinished plans and the search can be directed. Rules will have preconditions and effects like the actions in the planner. However these preconditions will match the plans and affect the organization of them. The rules may eliminate the idleness of one of the hands, may combine the actions to reduce steps of the operation or may change the order of actions so as to eliminate extensive transportation, they may as well impose the improvements regarding the design of the workplace.

A more compliant reasoning approach to the studies of motion economy is case-based reasoning. The motion economy and ergonomics studies are often presented as couples of original and improved methods. Extraction of the rules from these examples is a difficult process, however a case-based reasoning system may be constructed by storing these incidents as cases with proper indexing concerning the improvement reasons and methods. However the organization of a case, indexing and adaptation tasks must be analyzed further. The applicability of case-based reasoning method and its real advantages and disadvantages remain to be investigated.

Design of the Workplace

It should be clear by now that the design of the workplace is an indispensable part of motion economy. Special types of bins may be used for different tools such as rectangular or hopper type bins. Containers may be placed to appropriate locations considering the hand, which uses it, or the sequence of its usage in the operation. The planner or a module, constructed on top of it, has to make decisions regarding the places of equipment on the workbench as well as the characteristics of the equipment. However ordinary planning algorithms does not allow functions in the literals. A real valued function, such as coordinates in the work place or the dimensions of a tool, causes the search space to be infinite. The planner has to work with discrete valued literals.

Numerical values describing the workplace have to be represented by discrete values. The workplace may be divided to normal reach area, maximum reach area for the left and right hand. However terms like normal, maximum are vague concepts in human reasoning. A way to deal with this problem is to use fuzzy logic while introducing literals regarding the dimensions. Let **s** be a member of superset of fuzzy set of **F**. The degree of membership of **s** to the set **F** is a real value between 0 and 1, and is measured by a membership function **mF(s)**. Membership function is a “possibility” distribution defining the membership of the concept to the fuzzy set.

Suppose we have a rule having the form

IF (brush is thin) AND (few brushes will be used) THEN (use a narrow container)

We will look up for the membership values of the precondition statements, and minimum of the membership values will be assigned as the membership value for the outcome. The membership value of the outcome will determine the type of the container that will be used. There can be more than one rule, whose output submits a membership value for an object in the workplace. A way of finding the type of the container from its membership values must be devised. This task is sometimes called defuzzification. One possible method is the centroid method, where the final value of the concept is determined by finding the centroid of the union of the areas for the output value. There are numerous issues, which remain to be addressed, for employing fuzzy reasoning, and integrating it with the planner.

6. Conclusion

We have seen that work methods design dealt both with process planning and design of the operation method. Process planning is one of the major fields that AI planning is applied over the years. Process planning provides a fruitful domain for planning. However AI planning tools were not used in work study so far. Generation of high-level plans for robots and industrial manipulators is discussed in [9], [11]. Saving from time or considering ergonomics has not been the concern of these studies. Bimanual coordination is the title of the studies of cognitive scientists, regarding the coordination of the hands. These studies are not oriented to generate rules that will govern the manual operations. They usually present an experiment, which is conducted for showing the performances of the attendants in the repetitive tasks.

Although motion study has been used for workshop operations for decades, it requires intense examination of the job by specialists. The structure of the implementation is mostly composed of checklists. The job gets harder and harder as the number of primitive motions increases. Handling or aiding this work by computers will save valuable time and effort in methods design phase. Conventional methods, such as project scheduling, search only possible orderings of the tasks disregarding cognitive and ergonomic constraints. Planning for the ease of the worker is essential for reducing operational disorders and also productivity in repetitive tasks. As well as production, other sectors such as service can benefit from this study.

Architecture of this study will be composed of several approaches such as partial-order planning, rule-based reasoning and fuzzy reasoning. However we still continue the survey for possible methods, and did not begin to implement the system yet. Uncertainties related to the methods have not been totally resolved. This is partially due to the time elapsed from the start of the study and partially due to the lack of similar studies in the domain. More discussion is clearly needed before the realization of the system, however we will apparently keep resolving conflicts during the implementation, and towards the end of the study.

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