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Intelligent Systems Laboratory

PROCESS PLANNING

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What is Process Planning?
Methods and tools for getting from STOCK to PART

Machining Process
Process plan determines:
- Sequence of operations
- Resource required
  - machines
  - tools
  - fixtures

Process Planning: Overview
Input
Raw Material Components Activities Facts
Process Planning System
Knowledge Procedures Models
Process Plan
Machining Assembly Product Design Treatment Protocol
Question:
Is process planning domain dependent?

Answer:
Yes, the domain knowledge depend on the process domain, e.g., machining, assembly, semiconductor process, etc.

Basic approaches to automated process planning:

- Variant approach (GT based)
- Generative approach

Features

1. Form feature: a geometric feature of interest to the designer, such as a slot, hole, and so on.

2. Basic form feature: refers to the basic geometric feature of a part, usually of the same as the raw material.

3. Subfeature: a form feature defined for a basic feature, such as slot, hole, and so on.

4. Machining feature: a volume of material to be removed to produce a form feature.

Discussion of Process Planning Phases

1. Interpretation of Part Design Data

Features (continued)

5. Basic machining feature: a volume of material to be removed from the raw material to obtain a basic form feature.

6. Elementary machining feature: a volume of material obtained by decomposing the basic machining feature, or a volume of material that corresponds to a particular subfeature that is not decomposable.

7. Machining feature: consists of one or more elementary machining features that are removable in a single tool pass.
Sample Form Features and the Corresponding Machining Features

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Form feature</th>
<th>Machining feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane</td>
<td>Block</td>
<td></td>
</tr>
<tr>
<td>Slot</td>
<td>Block</td>
<td></td>
</tr>
<tr>
<td>Hole</td>
<td>Cylinder</td>
<td></td>
</tr>
</tbody>
</table>

Methods of Features Representation and Recognition

- Syntactic pattern recognition
- State transition diagrams
- Decomposition approach
- Knowledge-based approach
- Constructive solid approach
- Graph based approach

Knowledge-Based Feature Recognition

Rule 1
IF a hole entrance face exists
AND the face adjacent to the entrance is cylindrical
AND the next adjacent face is a plane adjacent to the cylinder
THEN the feature is a simple blind hole

Graph Based Feature Recognition

Geometry

Example: Rule for the recognition of a pocket

Rule 2
IF the graph is cyclic
AND it has exactly one node with the number of incident 0 arcs equal to the total number of nodes - 1
AND each other node is incident to exactly 3 arcs
THEN the corresponding feature is a POCKET

Example: Manufacturing features jointly with dimensions and tolerances
2. RECOMMENDATION OF MANUFACTURING PROCESSES

Example: Stock and part P

Rule 3
IF feature is a SLOT
AND tolerance = + 0.010 in
AND surface finish <= 94
THEN machining_process is END_MILLING
AND machining_direction is Z_Axis.

Rule 5
IF drilling process p3 is recommended for feature f5
AND drilling machines M1 that can perform process p3 is available
THEN use machine M1 to derive the feature f5

Frame 3
( DRILLING
  (AKO (Value DRILLING))
  (FRAME_LABEL (Value DRILLING))
  (TOOL_SELECTED (Value DRILL_BIT))
  (SMALLER_SIZE (Value D1 diameter))
  (LARGER_SIZE (Value D2 diameter))
  (MACHINE.SELECTED (Value MACHINE_M1)) )

Frame 4
((MACHINE_M1
  (AKO (Value DRILLING_MACHINE))
  (FRAME_LABEL (Value DRILLING_MACHINE))
  (MAX_AXIAL_LOAD (Value X))
  (MAX_POWER_ATTAINABLE (Value Y)) )

3. RECOMMENDATION OF ALTERNATIVE MACHINES, TOOLS, AND FIXTURES
4. PROCESS OPTIMIZATION

Taylor’s tool life equation

\[ t = \frac{\lambda C}{V^{\alpha} f^{\beta} a_p^{\gamma}} \]

where:  
- \( t \) is the tool life
- \( \lambda, C \) are constants for a specific tool/workpiece combination
- \( \alpha, \beta, \gamma \) are exponents for a specific tool/workpiece combination
- \( V \) is the cutting speed
- \( f \) is the feed rate
- \( a_p \) is the depth of cut.

Single-Pass Model

**Notation**

- \( t_{pr} \): total (machining, handling, and tool change) time for a prismatic part
- \( t_m \): machining time
- \( t_h \): material handling time
- \( t_t \): tool changing time
- \( t \): tool life
- \( C_{pr} \): production cost per part
- \( C_h \): setup cost for a batch of parts
- \( C_m \): total machine and operator rate
- \( C_r \): tool cost
- \( N_b \): batch size

**Model**

\[ \min t_{pr} = t_m + t_h + t \left( \frac{t_m}{t} \right) t_t \]

or in terms of cost

\[ \min C_{pr} = \frac{C_h}{N_b} + C_m \left[ t_m + t_h + t \left( \frac{t_m}{t} \right) t_t + \left( \frac{C_r}{C_m} \right) \right] \]

subject to:

- spindle-speed constraints:
  \( n_{w_{\min}} < n_w < n_{w_{\max}} \) (for the part)
  \( n_{t_{\min}} < n_t < n_{t_{\max}} \) (for the tool)
- feed constraint:
  \( f_{\min} < f < f_{\max} \)
- cutting force constraint:
  \( F_c < F_{c_{\max}} \)
- power constraint:
  \( P_m < P_{m_{\max}} \)
- surface-finish constraint:
  \( R_a < R_{a_{\max}} \)

Multi-Pass Model

**Notation**

- \( n \): number of machining passes
- \( a_i \): the depth of cut in machining pass \( i \)
- \( t_i \): the time required for machining pass \( i \)
- \( C_{pr_i} \): the production cost per part for the machining pass \( i \)

**Model**

\[ \min \sum_{i=1}^{n} \left[ t_i + \frac{C_{pr_i}}{n_b} \left( t_m + t \left( \frac{t_m}{t} \right) t_t \right) \right] \]

or in terms of cost per part:

\[ \min C_{pr} = \frac{C_h}{n_b} + C_m \left[ t_m + t_h + t \left( \frac{t_m}{t} \right) t_t + \sum_{i=1}^{n} \frac{C_{pr_i}}{n_b} \left( t_m + t \left( \frac{t_m}{t} \right) t_t + \left( \frac{C_r}{C_m} \right) \right) \right] \]

where:

\[ C_{pr_i} = C_m \left[ t_i + t \left( \frac{t_m}{t} \right) t_t + \left( \frac{C_r}{C_m} \right) \right] \]

and the subscript \( i \) represents the \( i \)-th pass subject to constraints and

- \( a_{\min} < a_i < a_{\max} \)
- \( a_i = \frac{a_i}{a_j} \)
Rule 6
If the depth of cut of feature $f_2$ is $\leq 2$ mm
AND surface finish class is $s_3$
AND tolerance class is $t_4$
THEN use the single-pass model for machining optimization

Rule 7
If the process is turning
THEN calculate machining time from the formula
$$t_m = \frac{l_w}{f} \frac{1}{n_w}$$
where:  $l_w =$ length of the surface to be turned
$f =$ feed rate
$n_w =$ rotational frequency of the part (rpm)

5. VOLUME DECOMPOSITION

Phase I
Divide the basic manufacturing feature (volume to be removed) into “bricks”

Stock and Part P

Phase II
Decomposition of the material volume to be removed

Decomposition of volume $V$ to be removed into volumes $v_1$, ..., $v_9$
by extending the existing planes.

Decomposition of volumes $v_1$, ..., $v_9$ into elementary machining features $e_1$, ..., $e_{18}$ by considering the depth of cut plane $p_1$. Plane $p_2$ is a tolerance base.
Question:
What limits the number of elementary features?

Answer:
The size of the matrix

6. SELECTION OF MANUFACTURING FEATURES

Simple Model

\[ \text{Min } \sum_{j \in J} c_j x_j \]
subject to:
\[ \sum_{j \in J} a_{ij} x_j \geq 1 \text{ for all } i \in I \]
\[ x_j = 0,1 \text{ for all } j \in J \]

Extended Model

\[ \text{Min } 3x_1+2x_2+x_3+x_4+x_5 \]
\[ x_1+x_3\geq1 \]
\[ x_1+x_2\geq1 \]
\[ x_5+x_2\geq1 \]
\[ x_1\geq1 \]

\[ \text{INTEGER 5} \]

Example

\[
\begin{array}{c|c|c|c|c}
  x_1 & x_2 & x_3 & x_4 & x_5 \\
  \hline
  V_1 & V_2 & V_3 & V_4 & V_5 \\
  \hline
  1 & 1 & 1 & 1 & 1 \\
  1 & 1 & 1 & 1 & 1 \\
  1 & 1 & 1 & 1 & 1 \\
  1 & 1 & 1 & 1 & 1 \\
  1 & 1 & 1 & 1 & 1 \\
  \hline
  x_1 & x_2 & x_3 & x_4 & x_5 \\
  \hline
  V_1 & V_2 & V_3 & V_4 & V_5 \\
  \hline
  1 & 1 & 1 & 1 & 1 \\
  1 & 1 & 1 & 1 & 1 \\
  1 & 1 & 1 & 1 & 1 \\
  1 & 1 & 1 & 1 & 1 \\
  1 & 1 & 1 & 1 & 1 \\
  \hline
\end{array}
\]

Each column "makessense" on its own

Notation

- \( I \) set of all elementary machining features of the part
- \( J \) set of all machining features \( V \)
- \( a_{ij} = \begin{cases} 1 & \text{if elementary machining feature } e_i \text{ corresponds to machining feature } V_j \\ 0 & \text{otherwise} \end{cases} \)
- \( T \) set of available tools for machining the part
- \( F \) set of available fixtures
- \( N_t \) upper limit on the number of tools to be used for machining the part
- \( J_t \) subset of machining features for which tool \( t \in T \) applies ( \( U J_t = J \) ) \( t \in T \)
- \( J_f \) subset of machining features for which fixture \( f \in F \) applies ( \( U J_f = J \) ) \( f \in F \)
- \( c_j \) removal cost of machining feature \( V_j \), \( j \in J \)
- \( p_t \) utilization cost of tool \( t \in T \)
- \( k_f \) utilization cost of fixture \( f \in F \)
- \( N_f \) upper limit on a number of fixtures to be used
Notation (continued)

1  if machining feature $V_j$ is selected, $j \in J$

\[ x_j = \begin{cases} 
1 & \text{if tool } t \text{ is selected, } t \in T \\
0 & \text{otherwise} \\
1 & \text{if fixture } f \text{ is selected, } f \in F \\
0 & \text{otherwise} \\
1 & \text{if machining feature } V_j \text{ is selected, } j \in J \\
0 & \text{otherwise} \\
\end{cases} \]

\[ x_{ij} = \begin{cases} 
1 & \text{for all } i \in I_j \\
0 & \text{otherwise} \\
\end{cases} \]

\[ y_{it} = \begin{cases} 
1 & \text{for all } t \in T_a \\
0 & \text{otherwise} \\
\end{cases} \]

\[ z_{if} = \begin{cases} 
1 & \text{for all } f \in F_b \\
0 & \text{otherwise} \\
\end{cases} \]

Model

\[ Z = \text{Min} \sum_{j \in J} c_j x_j + \sum_{t \in T} p_t y_t + \sum_{f \in F} k_f z_f \]

s.t.

\[ \sum_{j \in J} a_{ij} x_j \geq \lambda \text{ for all } i \in I \]

\[ y_t \leq N_t \text{ for all } t \in T \]

\[ x_j \leq |J_t| y_{it} \text{ for all } t \in T \]

\[ z_{if} \leq N_f \text{ for all } f \in F \]

\[ x_j = 0,1 \text{ for all } j \]

\[ y_t = 0,1 \text{ for all } t \]

\[ z_{if} = 0,1 \text{ for all } f \]

\[ \sum_{j \in J} x_j \leq 1 \]

\[ \sum_{t \in T} y_t \leq 2 \]

\[ \sum_{f \in F} z_{if} \leq 2 \]

\[ \sum_{j \in J} x_j \geq 1 \]

\[ \sum_{t \in T} y_t \geq 2 \]

\[ \sum_{f \in F} z_{if} \geq 2 \]

\[ x_1 + x_2 + x_3 + x_4 + x_5 \leq 1 \]

\[ y_1 + y_2 \leq 1 \]

\[ z_1 + z_2 \leq 1 \]

\[ v_1 + v_2 + v_3 \leq 1 \]

\[ v_4 + v_5 \leq 1 \]

\[ \sum_{j \in J} x_j \leq 1 \]

\[ \sum_{t \in T} y_t \leq 1 \]

\[ \sum_{f \in F} z_{if} \leq 1 \]

\[ e_{11} e_{12} e_{13} e_{14} e_{15} e_{16} e_{17} e_{18} \]

\[ v_1 + v_2 + v_3 \leq 1 \]

\[ v_4 + v_5 \leq 1 \]

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\[ v_4 + v_5 \leq 1 \]

\[ \sum_{j \in J} x_j \leq 1 \]

\[ \sum_{t \in T} y_t \leq 1 \]

\[ \sum_{f \in F} z_{if} \leq 1 \]

\[ x_1 + x_2 + x_3 + x_4 + x_5 \leq 1 \]

\[ y_1 + y_2 \leq 1 \]

\[ z_1 + z_2 \leq 1 \]
Additional Data

- vector $C = [c_{ij}]$ of machining costs
  $C = [5, 5, 2, 3, 1, 4, 5, 1, 5, 6, 4]$
- vector $T$ of tools
  $T = [t_1, t_1, t_3, t_2, t_3, t_1, t_1, t_2, t_3, t_1, t_1]$
- vector $F$ of fixtures
  $F = [f_1, f_1, f_2, f_2, f_1, f_1, f_1, f_2, f_2, f_1, f_1]$
- maximum number of tools to be used $N_t = 3$
- maximum number of fixtures to be used $N_f = 2$

SOLUTION:

- $x_1 = 1$, $x_5 = 1$
- $y_1 = 1$, $y_2 = 1$
- $z_1 = 1$, $z_2 = 1$

$v_1$ $v_2$ $v_4$

$v_3$

$\sum y_t \leq N_t$

$\sum z_f \leq N_f$

$\sum x_j = |J| \ y_t$

$\sum z_f = |F| \ z_t$

$\sum x_j = |J| \ x_f$

END

INTEGER 18
Solution

- $x_1 = x_2 = x_5 = x_8 = x_{10} = 1$
  with the corresponding machining features:
  $V_1 = \{e_1, e_2, e_3, e_4, e_5\}$, $V_2 = \{e_6, e_7, e_8, e_9, e_{10}\}$,
  $V_5 = \{e_{11}\}$, $V_8 = \{e_{18}\}$, $V_{10} = \{e_{12}, e_{13}, e_{14}, e_{15}, e_{16}, e_{17}\}$

- $y_1 = y_2 = y_4 = 1$
  with the corresponding tools $t_1, t_2, a \text{ and } t_4$ selected

- $z_1 = z_2 = 1$
  with the corresponding fixtures $f_1$ and $f_2$ selected

- Value of the objective function is $Z = 23$.

7. GENERATION OF PRECEDENCE CONSTRAINTS

Rule 9

IF machining feature $V_i$ can be accessed
only after machining feature $V_k$ is removed
THEN generate a precedence constraint $V_k \rightarrow V_i$

Rule 10

IF plane p $\in V_k$ is a tolerance base for
machining feature $V_i$
THEN precedence $V_k \rightarrow V_i$ is generated

8. SEQUENCING MANUFACTURING FEATURES
Algorithm 1 (Topological sorting)

Step 1. For i = 1 to n do [output the manufacturing features (vertices)].
Step 2. If every manufacturing feature has a predecessor, then stop [the precedence graph has a cycle and no feasible solution exists].
Step 3. Select a manufacturing feature Vi that has no predecessors.
Step 4. Output Vi.
Step 5. Delete the manufacturing feature Vi and all edges leading out of Vi from the precedence graph.
Step 6. End.

Example

Precedence Graph for Part P

Sequence Generated by the Topological Ordering Algorithm

Original Algorithm 1

Step 3. Select a manufacturing feature Vi that has no predecessors.

Modified Algorithm 1

Step 3'. Select a machining feature Vi that has no predecessors and that requires manufacturing resources most similar to the resources required by Vi.
Selection of Manufacturing Features

Notation

- $I$ - set of elementary machining features $e_i$
- $J$ - set of machining features $V_j$

- $a_{ij} = \{ 1$ if elementary machining feature $e_i$ corresponds to machining feature $V_j$
- $0$ otherwise

- $c_j$ - removal cost of machining feature $V_j$

- $x_j = \{ 1$ if machining feature $V_j$ is selected, $j \in J$
- $0$ otherwise

Simple Model Revisited

\[
\text{Min } \sum_{j} c_j x_j
\]

subject to:

- $\sum a_{ij} x_j \geq 1$ for all $i \in I$, $j \in J$
- $x_j = 0,1$ for all $j \in J$

Algorithm 4 (Chvatal)

1. Set the solution set $J^* = \emptyset$.
2. If $|V_j| = 0$ for all $j$, stop; $J^*$ is a solution.
3. Otherwise, find a subscript $k$ maximizing the ratio $|V_j| / c_j$ and proceed to Step 2.
4. Add $k$ to $J^*$, replace each $V_j$ with $V_j - V_k$, and go to Step 1.

Example

\[
\begin{align*}
|V_j| & = \text{cardinality of vector } V_j \text{ (number of non-zero elements in vector } V_j) \\
\text{heuristic approach} & = \text{Intuitive Explanation}
\end{align*}
\]

Intuitive Explanation

\[
\begin{align*}
\text{Max } |V_j| / c_j \quad & \quad = \quad \text{Min } c_j / |V_j| \\
\text{Min cost per unit} \quad & \quad (\text{elementary feature})
\end{align*}
\]
In Step 2, the set $J^* = \{5\}$ is updated and each $V_j$ is replaced with $V_j - V_5$, which corresponds to the removal of rows $e_1$, $e_2$ and $e_3$.

At Iteration 2 and Step 1 of Algorithm 4, the value $\max |V_j|/c_j = \max \{1/0.3, 1/0.7\} = 1/0.3 = 3.33$ with the corresponding $k = 4$ is computed.

The final solution is $J^* = \{4, 5\}$, i.e., machining features $V_4 = \{e_4\}$ and $V_5 = \{e_1, e_2, e_3\}$.

Algorithm Extension

Chvatal’s heuristic may be modified to reflect the cost $c_j$ change at each iteration of the algorithm.

Removal of rows, may reduce the $V_j$ content thus reducing $c_j$.