Control Problems of Manufacturing Systems

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Abstract - **The paper outlines some of the control problems and their solution of Flexible Manufacturing Systems (FMS).**

First, optimization problems are analyzed. General solution is presented. Connections to information systems (technological data bases), scheduling level problems (primary and secondary optimization) and adaptive control of machine tools are discussed.

Second, robot motion and optimal trajectory planning problems are analyzed.

Third, the new approach to FMS scheduling the use of Hybrid Dynamical Systems (HDS) is outlined. This, make possible to transform the operational research problem to a control one. The use of the method makes possible to realize very simple on-line, real-time scheduling. The outlined in the present paper planning method (based on the proposed by the author "periodic schedule" approach) is first published here.

The analyzed problems are deeply interconnected. Process parameters form engineering database for scheduling. The paper presents an example when quality solutions of FMS scheduling gives an opportunity to improve the overall system effectiveness.

1. CONTROL PROBLEMS OF MANUFACTURING SYSTEMS.

1.1. Introduction.

On Figure 1.1, a typical structure of a Flexible Manufacturing System (FMS) is given. FMS realizes integrated processing of material and information and has some kind of production planning sub-system. Flexible Cells might be the parts of the FMS which systems might be the parts of Computer Integrated Manufacturing (CIM) systems.

On Figure 1.1

- CAPP – Computer Aided Process Planning
- FCS – Finite Capacity Scheduling
- PCS – Process Control System

The most important ideas concerning CIM are:

- ERP – Enterprise Resources Planning
- MES – Manufacturing Execution System

In their frame the sub-systems are like:

- MRP – Material Requirement Planning
- FCS – see: as above
- Etc...

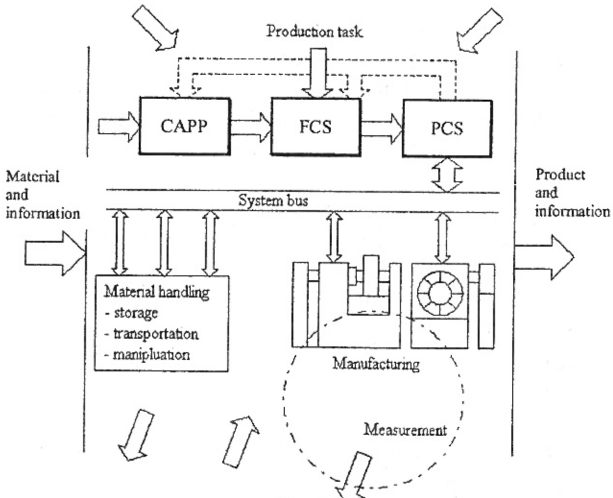

Fig. 1.1
Structure of FMS

The FMS and FMS processes planning and control problems involve the solution of huge number of engineering, management and interdisciplinary problems. In the present paper, as examples, a few of these will be analyzed.

1.2. Optimization of manufacturing processes.

Let us consider the simplest manufacturing data selection problem shown on Figure 2.1.

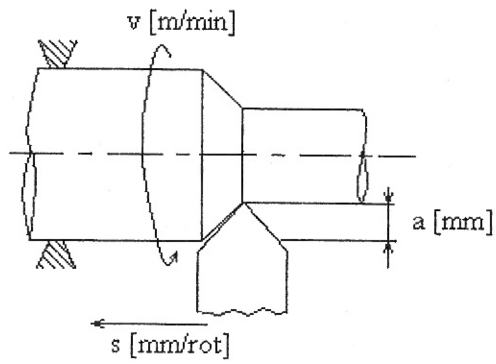

Fig. 2.1
Cutting process

This example demonstrating an external turning process is typical for data selection. Many other technologies (milling, griding, boring, etc.) may be treated similarly. The solution should be very quick because tremendous quantity at optimal data is necessary for even not to big production volumes.

We suppose that the depth of cut a [mm] is given. The optimal feed value s [mm/rot] and velocity (speed) value v [m/min] should be determined. The choice of the criterion of optimization was the topic of long discussions. We will not go into this problem and will use the minimum cost processing as the gool of planning.

2.1. State of the art

Early attempts to use computer technology for manufacturing processes optimization were mode by Goranszkij [1]. Early formulation of the mathematical model was given by Hitomi [2]. Etin (and others) [3] had provide rather general approach to optimization problem. Rembold, Nnaji, Storr [4] in 1993 still considers that: "There is no general solution either which exists for solving this kind of problem". General solution of the cutting process optimization was proposed by the author of the present plenary lecture [5, 6]. The following review is based on the cited works.

2.2. Mathematical model of optimization of cutting processes.

The mathematical model of cutting process consists of three parts:

a. System of constraints
b. Criterion of optimization
c. Tool life equation

a. System of constraints

The system of constraints characterizes the applicable region of the process parameters.
Homogeneous constraints:

$$Feed: s_{minimum} \le s \le s_{maximum}$$
$$Velocity: v_{minimum} \le v \le v_{maximum} \quad (2.1)$$
$$Rotational \cdot speed: n_{minimum} \le n \le n_{maximum}$$

Velocity and rotation are connected by

$$V = \frac{d\pi n}{1000}[m/\min]$$

Non-homogeneous constraints are, for example:

Main cutting force:

$$F_F = C_F a^{x_F} s^{y_F} v^{z_F} \le F_{F,Maximum}[N] \quad (2.2)$$

where,

C_F -- proper coefficient

x_F, y_F, z_F - are powers taken from engineering data handbooks, or obtained by experiments.

Cutting power:

$$\eta N = F_F v = C_F a^{x_F} s^{y_F} v^{z_F} v = = C_F a^{x_F} s^{y_F} v^{z_F+1} \le \eta N_{max} \quad (2.3)$$

where η is the efficiency of the motor.

Figure 2.2 demonstrates that after logarithmic transformation, the permissible domain of cutting may by obtained.

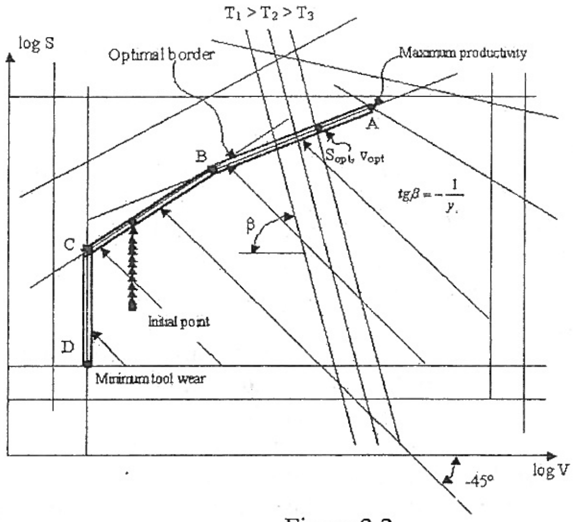

Figure 2.2
Optimal point determination

b. Criterion of optimization.

The cutting cost function can be divided two parts. K_I express the equipment, work power, etc... cost components, while the cost coming from the tool wear during the process is expressed by K_{II}.

$$K = K_I + K_{II} = C_M t_L + C_M C_T \frac{t_L}{T} = = C_M t_L\left(1 + C_T \frac{1}{T}\right)[money\ unit] \quad (2.4)$$

where,

C_M – manufacturing cost per unit time [money unit/min]

t_L – time for manufacturing [min]

$$t_L = \frac{L}{sn} = \frac{L}{s\frac{1000v}{d\pi}} = C_L \frac{L}{sv}[\min] \quad (2.5)$$

C_T – cost coefficient for estimating the tool wear cost effect [min]

$$C_T = \frac{K_I}{C_M} + t_{ch} \quad (2.6)$$

t_{ch} – is the tool change time (related to one edge)

K_I – is the tool cost for one edge [money unit]

Figure 2.3 demonstrates the two components of the cost function.

c. Tool life equation

We suppose that the extended Taylor equation is valid:

$$T^m = \frac{C_V}{a^{x_V} s^{y_V} v} \quad (2.7)$$

where,

m – Taylor coefficient (usually $0.15 \le m \le 0.3$ or close to this value)

C_V, x_V, y_V – are the properly determined, corresponding coefficients

Note: the value of x_V and y_V are very close to the value of m, but they are almost always less than one.

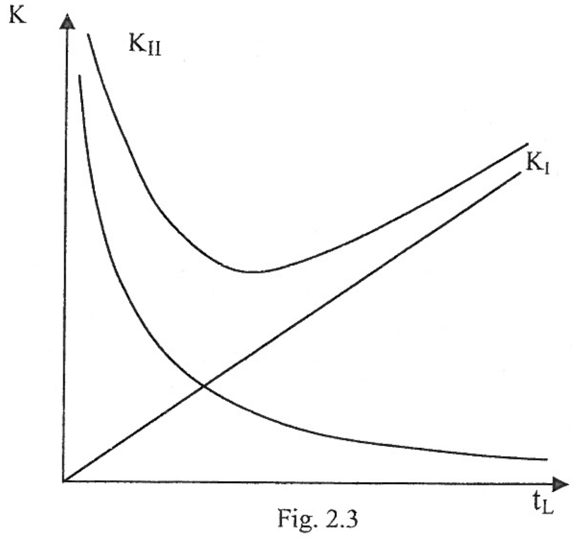

Fig. 2.3
Components of the cost function

2.3. Optimization theorems

Using logarithmic transformation for the equations forming the border of the permissible domain of cutting one gets the boundary consisting from piecewise linear sections.

First theory of optimization

The optimal point is on the border of the permissible domain of cutting in the points where -45° lines from the domain are coming (see on Fig. 2.3).
The manufacturing velocity affects the tool life much more then the feed. On the lines with -1 slope (-45°) the processing time is constant (sv = constant). From that the proof of theorem trivially follows.

Second theory of optimization

The optimal point on the upper and the lower branch of the optimal border is unique.

2.4. Determination of the optimal point

It is easy to prove (see [5, 6]) that the tool lives in local optimal points for the sections of the optimal border are

$$\left(T_{opt}\right)_i = \frac{1 + y_v N_i - m(1+N_i)}{m(1+N_i)} C_T \qquad (2.8)$$

Where

$$N_i = -\frac{z_i}{y_i} \qquad (2.9)$$

if the

$$s^{y_i} v^{z_i} = C_i \qquad (2.10)$$

border line in considered.

Based on (2.8) it is very easy to find the optimal point on the optimal border. The optimal point may only be A, B, C or D on Figure 2.2. or the only one point where (2.8) is satisfied. Beginning search from A if $(T_{opt})_A$ is less than T_A point A is optimal. If not, but among A and B exists a point where (2.8) is satisfied this is the optimal point. If not the same is researched for point B, and so on.

2.5. Discussion of optimality.

It is easy to recognize that by proper choice of C_T coefficient value different manufacturing strategies could be realized. At $C_T \equiv 0$, or properly small value maximum production can be obtained. By big C_T values proper tool economy regimes may be established. Among the optimal cost and maximum production point the point corresponding to maximum profit rate may be found (see: Somlo [7]).

2.6. Adaptive Control Constraints.

It is a great challenge for manufacturing industry to develop and use machine tools, which own control loops for safety or quality assurance.

Because, the relations of the system of constraints represent different physical quantities which are constrained to provide safety and quality issues, it is a real opportunity to build control loops which automatically realize these issues, even in the case of high perturbances. It is clear that without these control loops only rather conservative computed process parameter values may be used.

On Figure 2.4 a multiloop control architecture is shown to demonstrate the nature of systems of this kind.

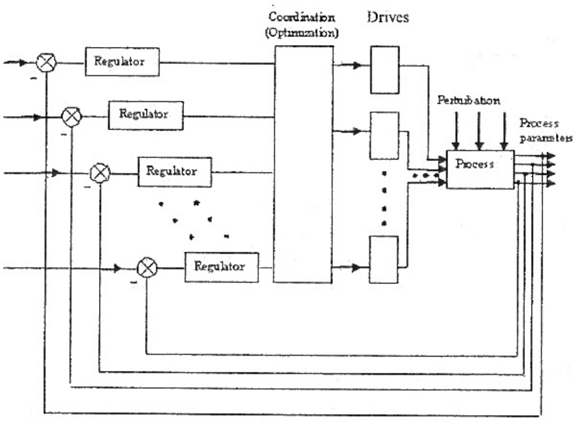

Fig. 2.4.
Multiloop control system

2.7. Adaptive Control Optimization.

Above the optimization of process data was analyzed. It was supposed that the depth of cut "a" is known (and given). Also, the mathematical model other parameters were supposed to be known. For example: the C_F coefficient for main cutting force, or the Taylor tool life equation coefficient and powers.

In case of high perturbations the "a" and "C_F" values (even x_F, y_F, z_F) can be identified. Much more complicated task is the tool life equation parameters identification. But, as the sensor technology develops (e.g. laser measurement technologies), in last time, these rather complicated measurement technologies have chances to be applied. If the identification problems solved, the optimization can be carried out "on-line". This way is demonstrated on Figure 2.5. An early example is the Makino MCC 100-AC (see: [6]).

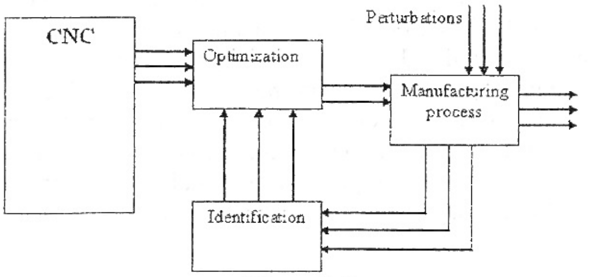

Figure 2.5
Adaptive Control Optimization

A rather challenging approach to the some problem is to realize ACO as follows. Having the optimization method demonstrated on Figure 2.3 and multi-loop feedback control systems as shown on Figure 2.4, ACO may be realized in rather simple way. Setting initial point inside the permissible domain the control loops will force this point to go into direction of optimal border. When the first constraint is meet the increase of feed value stops. Only here an identification problem should be solved. Namely, to which side to go (increase or decrease cutting velocity) to meet optimal for the given constraint tool life value.

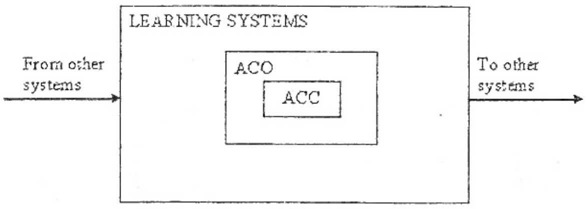

Fig. 2.6
ACC – ACO – Learning Systems – DATABANKS

2.8. Learning systems.

Having an ACO like system, or even a simpler multi-loop ACC system, gives the opportunity to use learning approaches to identify model parameters. Such attempt was e.g. the MONKEY system built by Monostori [9].

The learning systems may be interconnected to form a network. The data may be organized into technological databanks. The hierarchy of ACC, ACO and learning systems is shown on Figure 2.6.

Huge information massive may be built behind the simple machine tools to increase their effectiveness.

This is the challenging picture of the future instead of materials data handbooks which are most frequently the only helps to solve similar problems.

2.9. Primary and secondary optimization.

On Figure 2.7. GANTT diagrams are shown for a real production situation when, because the task scheduled to j-th machine group may not be processed not being finished an h-th machine group. On machine group j idle time arose. The conditions of the mathematical model given above are not valid any more. Indeed, an optimal compromise wanted to be achieved among cutting intensity and tool wear. But, here $C_M t_L$ value does not give the real cost of tool utilization, because the tool is "occupied" for t_L+It (It is the idle time value). (Set – up issues can be included, too).

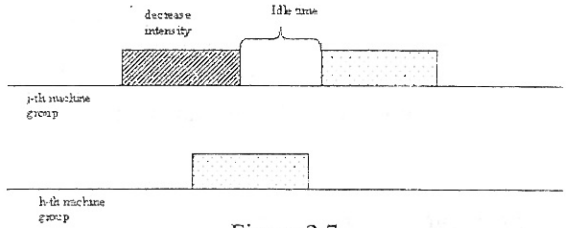

Figure 2.7
GANTT diagrams

It is a trivial way of economy to decrease the intensity of cutting. In this way significant tool economy may be realized. But, the decrease may be realized in many ways. It is proved in [5, 6] that the optimal way is to use the optimal tool life approach of optimization as it was described above then.

$$T_{opt\,sec} = (1 + \lambda_r)T_{opt\,pr} \qquad (2.11)$$

Relation (2.11) was obtained using the Lagrange method of conditional extremums [5, 6].

Not only the tool economy problem may be handled in this way, but, bottleneck situations may be solved or synchronization of tool lives of several instruments may be realized, etc.

Where $T_{opt\,pr}$ is the optimal tool life for the original problem. $T_{opt\,sec}$ is the modified optimal tool life. For the optimal problem (primary optimization $\lambda_r=0$. Then, $\lambda_r=k\Delta\lambda_r$ (k=1,2,3,)) is applied until the solution is obtained.

3. ROBOT MOTION PLANNING.

One of the most important problems of advanced robot application is the motion planning. In robotics many tasks are concerned with the solution of contour following problems. The quality of the solution of motion planning is a basic issue. It seems to us that the parametric method (see e.g.: Shin and McKay [10]) gives an universal solution for motion planning problems.

3.1. State of the art.

The above cited authors and others in the middle 80-ies proposed the parametric method of path planning, with the length of path as parameter. This approach gives a very general solution for this class of problems. The minimum – time problem solution was published in Somlo [11] (see also [12]). Recently, as it will be outlined, trajectory planning problems can be solved, realizing different goals, very effectively. Detailed reviews may be found in [12].

3.2. Parametric method of robot motion planning.

Let us consider Figure 3.1.

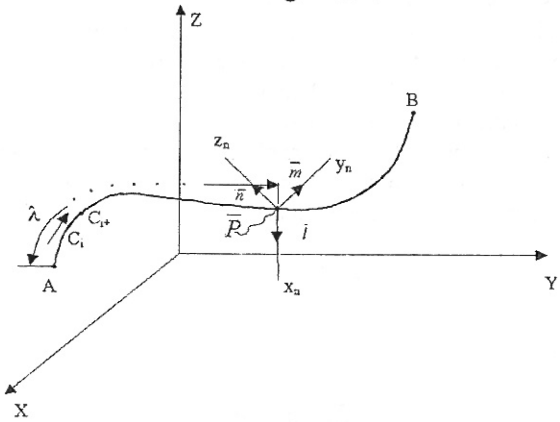

Figure 3.1
Robot motion planning

The x, y, z are the world coordinates axes forming the frame the application tasks should be planned in. The x_n, y_n, z_n are the working frame coordinate axes by the proper position (translation and orientation) of which the application tasks are realized.

Let us use

$$\bar{P} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} \text{ and } \bar{\bar{R}} = \begin{pmatrix} \bar{l} \\ \bar{m} \\ \bar{n} \end{pmatrix} \qquad (3.1)$$

The $\bar{P}$ vector characterizes the translation motion of the center of the working frame. The $\bar{\bar{R}}$ matrix consists from the unit vectors of the working frame axes.

$$\bar{l} = \begin{pmatrix} l_x \\ l_y \\ l_z \end{pmatrix}; \qquad \bar{m} = \begin{pmatrix} m_x \\ m_y \\ m_z \end{pmatrix}; \qquad \bar{n} = \begin{pmatrix} n_x \\ n_y \\ n_z \end{pmatrix}; \qquad (3.2)$$

Three independent components from l_x, l_y, l_z, m_x, m_y, m_z, n_x, n_y, n_z (for example: n_y, n_z l_x, etc) determines in any time instant the orientation of the working frame. Let us use for the translation coordinates x_1=x, x_2=y, x_3=z and for the components determining the orientation x_4, x_5, x_6. In the case of 5D problems only x_4 and x_5 should be given.

As it is well known vector $\bar{P}$ and matrix $\bar{\bar{R}}$ can be determined as the components of homogenous transformation matrices. These may be obtained using the Denavit – Hartenberg method or others.

The application planner provides information about geometry of the path, which should be realized. The most convenient form of representation of this information is the parametric form. A convenient parameter is the path length λ. Let two point C_i and C_{i+1} on the path be given. Let us use linear interpolation. Then given the elementary path length is

$$\Delta\lambda = \sqrt{\begin{array}{l}(x_{1,i+1} - x_{1,i})^2 + (x_{2,i+1} - x_{2,i})^2 + \\ + (x_{3,i+1} - x_{3,i})^2\end{array}} = \qquad (3.3)$$

$$= \sqrt{\begin{array}{l}(x_{4,i+1} - x_{4,i})^2 + (x_{5,i+1} - x_{5,i})^2 + \\ (x_{6,i+1} - x_{6,i})^2\end{array}}$$

So the path lengths can easily be computed independently of the form in which the path definition was performed (analytical or any form of numerical).

The path lengths can be computed also when other then linear interpolation is used.

So, the coordinates values can be expressed in parametrical way. In this way it is possible to determine

$$x_1 = x_1(\lambda), \quad x_2 = x_2(\lambda), \ldots, x_6 = x_6(\lambda) \qquad (3.4)$$

Realizing robot motions the inverse transformations should be performed. For the solution of that powerful methods are known. Homogeneous coordinates transformations apparatus can widely be used.

Considering serial robot and using

$$\bar{q} = \begin{pmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \\ q_5 \\ q_6 \end{pmatrix} \qquad (3.5)$$

for joint coordinates vector, inverse transformation results:

$$\bar{q} = \bar{q}(\bar{x}) \qquad (3.6)$$

Because $\bar{x} = \bar{x}(\lambda)$, it is possible to determine the $\bar{q} = \bar{f}(\lambda)$... functions.

That is

$$q_i = f_i(\lambda) \qquad (3.7)$$

i=1,2,3,4,5,6
can be determined.

Let us consider an example. This is the cylindrical robots 2-nd and 3-rd joint. Sometimes, similar devices are named polar manipulator.

On Figure 3.2 such device is shown

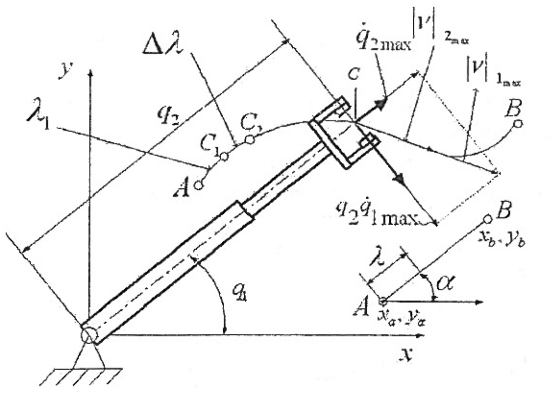

Fig. 3.2
Polar manipulator

It is clear, here, that for point "C", the equations of direct geometry are (motions in 1-st quarter are considered, only):

$$x = q_2 \cos q_1 \qquad y = q_2 \sin q_1 \tag{3.8}$$

The equations of inverse geometry are:

$$q_1 = arctg\frac{y}{x} \qquad q_2 = \sqrt{x^2 + y^2} \tag{3.9}$$

If moving along a straight line among A and B.

$$q_1 = arctg\frac{y_A + \lambda\sin\alpha}{x_A + \lambda\cos\alpha} \qquad q_2 = \sqrt{(x_A + \lambda\cos\alpha)^2 + (y_A + \lambda\sin\alpha)^2} \tag{3.10}$$

So,

$$f_1(\lambda) = arctg\frac{y_A + \lambda\sin\alpha}{x_A + \lambda\cos\alpha} \qquad f_2(\lambda) = \sqrt{(x_A + \lambda\cos\alpha)^2 + (y_A + \lambda\sin\alpha)^2} \tag{3.11}$$

Let consider any two points C_1 and C_2 in any path. The λ_1 value is supposed to be known. $\Delta\lambda$ can be computed according to equation (3.2). The length

$$\lambda_2 = \lambda_1 + \Delta\lambda \tag{3.12}$$

$$f_1(\lambda_2) = arctg\frac{y_{C2} + \Delta\lambda\sin\lambda}{x_{C1} + \Delta\lambda\cos\lambda} \qquad f_2(\lambda_2) = \sqrt{(x_A + \Delta\lambda\cos\alpha)^2 + (y_A + \Delta\lambda\sin\alpha)^2} \tag{3.13}$$

$$\alpha = arctg\frac{y_{C2} - y_{C1}}{x_{C2} - x_{C1}}$$

The functions $f_1(\lambda), f_2(\lambda)$ can easily be determined for any path.

3.3 Trajectory planning

3.3.1 Time optimal cruising trajectory planning

The task of time optimal cruising trajectory planning is the determination of velocities values, which provide the motion in any path with minimum time. Let consider the above example on Figure 3.2. If is easy to recognize that the time of motion on the path will be minimum, if in every point the absolute value of velocity is at its possible maximum value. In Figure 3.2 it is shown that the maximum values of joint velocities determine two different maximum values for the absolute value of velocity. Clearly, the minimum of these two values can only be realized. So, this minimum will be the time-optimal cruising velocity for the given point, that is the given parameter λ. The values of this velocity depend on the path geometry and on the maximum velocities of the joints.

Formulating the problem in general, at the use of parametric method at motion planning any joint coordinates can be obtained as

$$q_i = f_i(\lambda) \tag{3.14}$$

i=1,2,3,4,5,6.

So,

$$\dot{q}_i = \frac{dq_i}{dt} = \frac{\partial f_i(\lambda)}{\partial\lambda}\left(\frac{d\lambda}{dt}\right)_i \tag{3.15}$$

Taking $\dot{q}_{i\max}$

$$|v|_{i\max} = \frac{\dot{q}_{i\max}}{\dfrac{\partial f_i}{\partial\lambda}} \tag{3.16}$$

i=1,2,3,4,5,6

$\dfrac{\partial f_i}{\partial\lambda}$ can be approximated as

$$\frac{f_i(\lambda + \Delta\lambda) - f_i(\lambda)}{\Delta\lambda} \tag{3.17}$$

i=1,2,3,4,5,6

The determination of $f_i(\lambda+\Delta\lambda)$, $f_i(\lambda)$, $\Delta\lambda$ is involved in computations which necessary for the realization of the motion along the path. So, in every moment

$$|v|_{opt} = \underset{i}{Min}\left\{|v|_{1\max}, |v|_{2\max}, \ldots, |v|_{6\max}\right\} \tag{3.18}$$

can easily be determined.

Applying to cylindrical manipulator for close points with coordinates x_i, y_i; x_{i+1}, y_{i+1} results

$$|v|_{1\max} = \frac{\dot{q}_{1\max}\Delta\lambda}{arctg\dfrac{y_{i+1}}{x_{i+1}} - arctg\dfrac{y_i}{x_i}} \tag{3.19}$$

$$|v|_{2\max} = \frac{\dot{q}_{2\max}\Delta\lambda}{\sqrt{x_{i+1}^2 + y_{i+1}^2} - \sqrt{x_i^2 + y_i^2}} \quad (3.20)$$

$$|v|_{opt} = Min\left\{|v|_{1\max},\ |v|_{2\max}\right\} \quad (3.21)$$

Because, all of the quantities in (3.19) and (3.20) are necessary to be computed at path realization, it is very easy to compute $|v|_{opt}$ in every point. Then,

$$\Delta t = \frac{\Delta\lambda}{|v|_{opt}} \quad (3.22)$$

should be computed and with this the motion planning procedure is finished.
That is, the

$$q_1 = q_1(t)$$
and
$$q_2 = q_2(t) \quad (3.23)$$

functions (inputs of drives) are determined.
If is obvious that for higher dimension problems the procedure is the same. That is, based in Equation (3.16) and (3.18) the time-optimal trajectory.

$$|v|_{opt} = v(\lambda)_{opt} \quad (3.24)$$

can easily be obtained and the

$$t = \int_0^{\lambda} \frac{d\lambda}{v(\lambda)_{opt}} \quad (3.25)$$

mapping can be performed. Accordingly, the

$$q_{iopt} = q_i(t)_{opt} \quad (3.26)$$

i=1,2,3,4,5,6

inputs of the robot joints drives can be determined.

3.3.2 Phase plane diagrams

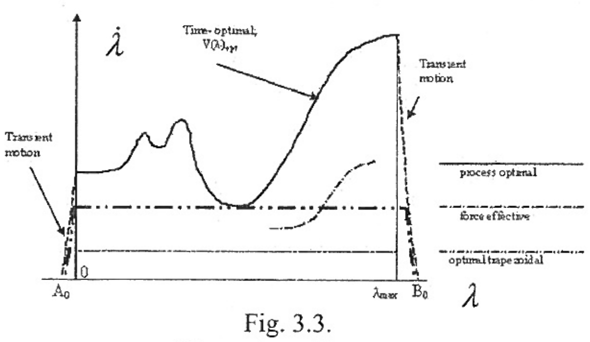

Fig. 3.3.
Phase plane diagram

If is convenient to use the $(\lambda, \dot{\lambda})$ phase plane diagrams for systems processes planning. This is demonstrated on Figure 3.3.

Clearly, no velocity values above the $v(\lambda)_{opt}$ curve can be realized. Below this, different curves, realizing different motion strategies can be applied. The **optimization of technological process** can be performed exactly as it was described in a section 2.4 of the present paper.

It is a very interesting opportunity to realize **force effective planning** (see:[12]). This is based on keeping the overall kinetic energy of the manipulator constant. If this is provided, the consequence is that in the given point of the path the maximum force along the tangent direction can be realized. This is due to the fact that the torques of the drives are not used for the change of kinetic energy, but to develope acting force.

The **optical trapezoidal velocity profile** is just the maximum trapezoidal profile which can be "embedded" into $v(\lambda)_{opt}$ profile.

3.3.3 Automatic trajectory planning

A new opportunity for trajectory planning is the automatic performance of the procedures. The developed by us system (see [19]) works without the necessity of the development of detailed programs. Just, the following commands should be introduced:

- TIME – OPTIMAL
- PROCESS OPTIMAL
- FORCE EFFECTIVE
- OPTIMAL TRAPEZOIDAL

The developed sub-programs provide the proper velocity profiles.

3.4 Advanced control

The desired input to robot joints drives

$$q_{id} \quad (3.27)$$

i=1,2,...,n
may be determined as it was outlined above.

Different kind of smoothing, forming algorithms can be used to realize different practical requirements concerned with the quality of the motion.

How well the joints can follow the required paths, trajectories depend on the quality of the control of the drives. Frequently, simple P, or PD control algorithms result good quality processes. In more sophisticated cases computed torques method and model reference adaptive control (MRAC) can be used with high effect. Especially promising approach is the use of asymptotically stable MRAC [12].

4. HYBRID DYNAMICAL APPROACH TO FLEXIBLE MANUFACTURING SYSTEM (FMS) SCHEDULING.

Until now, the technological processes were in the center of our attention. As a final parameter of planning of those, the time of performing the processes were obtained. This information forms an engineering database for solving scheduling tasks. Of course, not only the manufacturing data but, transport, manipulation times can be included in databases. A very important set of information is the group of set-up times. Having the data, the manufacturing equipment scheduling should be solved. In classical manufacturing systems, the batch processing kind of tasks were the most common. The different part types series, containing given number of parts, visited the consecutive machine groups (according to given sequences). The time sections dedicated to manufacture the given, different parts on different machine groups formed the schedule.

Schedules could be given by Gantt diagrams, or by tables (or by both).

The planning of schedules is an operation research task. Mathematical programming, or heuristic methods can be used for the solution. The order for scheduling comes from the MRP (Material Requirement Planning) system. The solution of optimization problems on MRP level and the MRP ↔ Scheduling interconnection are important problems, but not discussed here.

The connection of scheduling with process planning is obvious. In section 2 of the present paper the primary and secondary optimization problems were discussed. There are other deep connections and opportunities involved in this connection, too.

At the classical manufacturing, usually, the set-up times have high values. Nevertheless, in industrial practice, the series division and overlapping manufacturing are widely applied. Clearly, the benefits of series division compensate the losses caused by set-ups in these cases. By the spread of automation the situation changes. The set-up times are getting smaller (the transport, manipulation, etc. times, too). Nevertheless, the scheduling methods did not follow this development. Namely, as far as we know, there do not exist any general approach to the use of series division and overlapping production.

4.1 State of the art

The FMS scheduling formulated as a control problem was given in Perkins, Kumar [13], general theory of hybrid dynamical systems (HDS), (the solution deep analysis of periodic processes in those and a number of other problems) was given in Matveev, Savkin [14]. Many other works were concerned with different aspects of HDS. A more detailed overview can be find in Somlo [15].

4.2 A simplified mathematical model

A mathematical model for FMS scheduling using HDS can be found in [15,16,17]. Here only the basic quantities will be described.

The task is to produce i = 1,2,...I part type with series consisting from n_i (i = 1,2,...I) pieces during the scheduling time period $0 - T_{sch}$.

The production system consists from m = 1,2,...M machine groups (homogeneous sections).

The processing time of a part type piece is τ_{im} (i = 1,2,...I, m = 1,2,...M). Here only that case is considered when revisiting to the machine group is not allowed. But, the results can easily be generalized for the opposite case.

4.3 Hybrid dynamical approach (HDA)

Let us outline some basic points of HDA use.

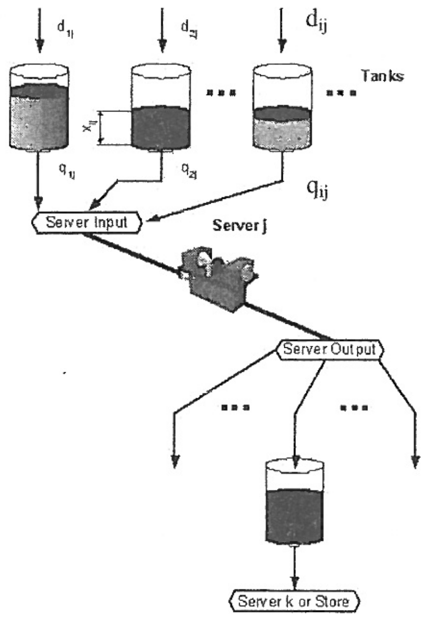

Fig. 4.1.
Fluid analog of the Flexible Manufacturing Systems processes

Consider a system given in Figure 4.1. This is a continuous analogue of a part of a Flexible Manufacturing System.

There are a number of tanks which are supplied with fluid. The incoming fluid flow rates are d_{1j}, d_{2j}, ..., d_{ij} at the server identified with index j. The servers are intelligent. It means that they drop the content of tanks in different rates. That is, from every tank the fuel is dropped with a specific rate q_{ij}, (i =1,2,3,.... I). The fuel may arrive from the central buffer, or from other servers. The fluid from a server may go to any of the tanks of the other servers, or to the output of the system, which can be represented, by the final product store. Here, it is supposed that a given flow does not return to the same server. The processes in this kind of systems correspond to general job shop type production in FMS. The servers are the machines, or more generally the groups of equivalent machines. The tanks are the buffers. The demand rate is the determination of the production task, but not in the usual form, when the number of parts required during the production period is given. But, it is given as the number of parts to be produced during the time unit. The dropping rate corresponds to the part production rate, that is, to the number of parts produced during the time unit. It is easy to recognise that if the production time of a part is τ_{ij} , then $q_{ij}=1/\tau_{ij}$. (i-is the index of part type, j-is the index of the machine group). The fluid levels in the tanks are the buffer contents. As it was mentioned, the fluid analogue represents a continuous system. The role of the server in Figure 4.1 is that at its input all of the values q_{ij} are present. But, the output, at any moment, is only one of these (or zero, because set-up).

4.4 Demand rate determination

We used the same demand rate for a series of part on all of the servers. That is

$$q_{im} = q_i \quad i = 1,2,...I \quad m = 1,2,..M \tag{4.0}$$

It can be proved that the demand rate can be determined as

$$\frac{n_i}{T_{sch}} \le d_i \le Min \left\{ \frac{1}{\underset{m}{Max}(\tau_{im})}, \frac{n_i}{\underset{m}{Max}(\mathrm{tl}_m)} \right\} \tag{4.1}$$

Where tl_m is a component of the so called machine group load vector (m = 1,2,...M).

$$\mathrm{tl}_m = \sum_{i=1}^{I} n_i \tau_{im} \tag{4.2}$$

m = 1,2,...,M

The bottleneck machine group is the one for which

$$\mathrm{tl}_m = Max\mathrm{tl}_m = M\mathrm{tl}_m \tag{4.3}$$

According to Relation (4.1) one of the components determining the demand rate is $M\,\mathrm{tl}_m$

Let us use the following method for demand rate determination.

Let

$$d_i = \frac{n_i}{M\mathrm{tl}_m} k \tag{4.4}$$

Where k is reservation coefficient. For example, for effective scheduling k = 0,95 - 0,85.

The determination of demand rate is different from (4.4) if

$$\frac{1}{Max(\tau_{im})} < \frac{n_i}{Max(tl_m)} \tag{4.5}$$

Then

$$d_i = \frac{1}{Max(\tau_{im})} k_i \tag{4.6}$$

is applied. Where k_1 - is the reserve coefficient (k_1 can be chosen in the same range as k).

We suppose that

$$\frac{n_i}{T_{sch}} < \frac{n_i}{Max(\mathrm{tl}_m)} \tag{4.7}$$

is always satisfied because the MRP sub-system always provides this.

So in relation (4.4)

$$k \ge \frac{M\mathrm{tl}_m}{\mathrm{T}_{sch}} \tag{4.8}$$

should always be satisfied.

If

$$\frac{n_i}{T_{sch}} > \frac{1}{Max(\tau_{im})} \tag{4.9}$$

The task is inconsistent (the system is unstable).

4.5 Determination of part flow processes

Let us consider Figure 4.2.

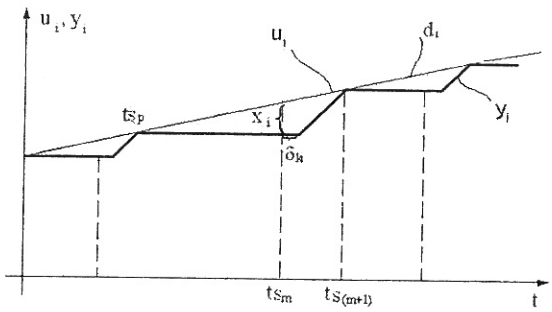

Fig. 4.2

Input and output buffer contents of machine groups

On this the part demand for a part type u_i and the part production process y_i is demonstrated i = 1, 2,..., I. At time instant tS_m the buffer at some of other part types produced on the given machine group "m" become empty. After the set-up time δ_k (k is the part index produced until tS_m) production of part type i begins.

If can be proved [15,16,17] that

$$tS_{(m+1)} = \frac{tS_m + \delta_{ki} - tS_p d_i \tau_{im}}{1 - d_i \tau_{im}} \tag{4.10}$$

Having some starting procedure (see [15]) using recursive equation (4.10) the switching time instants for all of the part types can be determined. So, the part production processes become known. On the figure 4.2 the part demand is known as a sloped line (with demand rate as the slope). Generally speaking, this can be proved only if the given operation is the first for the part type and the rough part comes from the central buffer. In other case, if the output parts would be introduced to the input buffer of the consecutive machine group the input flows would be abrupt. These, could not provide the required input buffer content patterns. This problem can be handled by using the controlled buffer technique (see [15, 16, 17]). The essence of this is that, so called, auxiliary buffers are introduced into the structure of the system. These buffers contain extra part pieces which are delivered into "basic" buffers when there is not part production to cover the part demand. The auxiliary buffers are not real physical extra buffers, but, virtual, ones.

This means, that a part of the real, physical buffer is treated as auxiliary the other as basic storing capacity. The pieces, without physical motion, are highlighted as belonging to one or other type. The allocation might be on central or local storing places.

The only organization restriction is to provide the part piece of the machine group when it comes to processing.

Using the controlled buffer technique at all of the machine group the same demand pattern is introduced. In fact, the demand pattern differs only in that respect, that in different machine groups the processed part type controls may be different. It can be recognized that the flows totally "full" the processing time with "processing"; "set-up"; "processing", "set-up"... sections (no idle machine-group sections are present). The switches on bottleneck machine group sections are less frequent than of the others.

4.6 Planning of part flow processes

It can be proved that for stable systems the part flow processes converge to periodic ones (see e.g. [14]). Both the transient and periodic part flow processes can be considered for planning of working regimes. But, the periodic processes are much more attractive for planning,

The following materials are based on Somlo, Savkin [18].

It can be proved that at the use of **cyclical switching law**, (using (4.4) for demand rate determination) periodic processes arise, the period of which on the bottleneck machine group are

$$T_{per} = \frac{\sum \delta_{jk}}{1-k} \tag{4.11}$$

where $\Sigma\delta_{jk}$ is the sum of the set-up times at the processing of the different part types.

If short transient process can be realized (using a proper starting procedure), it is easy to show that the number of part pieces during a period is

$$n_{iper} \approx \frac{k\sum \delta_{jk}}{(1-k)Mtl} n_i \tag{4.12}$$

Relation (4.12) gives an excellent and simple opportunity for systems flows planning. Choosing a proper k reserve coefficient value, the number of part pieces during a period can be estimated. The buffer sizes (auxiliary and basic together) should slightly higher than this number.

So, the flows planning procedure can be very simple. Let suppose e.g.:

$$\frac{\sum \delta_{jk}}{Mtl} = 0.005$$

and choose k = 0.95

Then $n_{iper} \approx \frac{1}{10} n_i$

If the system is stable at the given k value the completion time is about 5% of the global minimum. The necessary buffer size is about the tenth of that at batch processing.

It is a challenging opportunity to increase the k value closer to 1. It will decrease the completion time, but increase the period of processes and part type pieces number produced during a period. Opposite effect can be realized by decrease of k value. For example: if k = 0.9 the completion time will be about 1,1...1,15 of global minimum and

$$n_{iper} \approx \frac{1}{22} n_i$$

Until now we were considering only the processes on the bottleneck machine group. It can be proved that the periodic processes have the time periods on the different machine groups

$$\left[T_{per}\right]_m = \frac{\left[\sum \delta jk\right]_m}{1-k\dfrac{tl_m}{Mtl}} \tag{4.13}$$

Where $[\Sigma\delta_{jk}]_m$ is the sum of set-up times for machine group with index m. Accordingly

$$(n_{iper})_m \approx \frac{\left[\sum \delta_{jk}\right]_m k}{Mtl} = \frac{\left[\sum \delta_{jk}\right]_m k}{\left(1-k\dfrac{tl_m}{Mtl}\right)Mtl} \tag{4.14}$$

So, the less the load the smaller the time period (the higher the frequency) and the number of part pieces processed during a period. These features might be not advantageous. Too frequent set-ups, even not increasing the overall processing time, might not be useful. There are several ways to eliminate this feature. One of the most promising is the use of regularizibility [14]. This approach uses a seemingly very dangerous way. That is the proper, artificial increase of set-up times. Indeed, considering relations (4.13) and (4.14) it can be recognized that by increasing $[\delta_{jk}]_m$ the unnecessarily small $[T_{per}]_m$ and $(n_{iper})_m$ values can be increased to the proper values. Because, the capacity surpluses of not bottleneck machine groups may not be utilized, this way seems very promising. (It is supposed that the machine groups balancing problem was already solved on MRP level. So, there are no means to utilize capacity surpluses).

4.7 On-line, real-time control

The outlined planning methodology may result an extremely simple approach may result to on-line, real-time control of scheduling level processes. Indeed, determining the proper k value, the demand rates can be determined as outlined before. The part type pieces according to the demand are highlighted in the corresponding buffers. (The auxiliary buffers may need some initial fill-up process). The processing goes on the machine group according to the switching law (e.g.: cyclical switching). The highlighted (in basic buffer) parts are delivered and manipulated to the working position and processed. When there are no highlighted part pieces in some "active" buffer, automatic set-up and switch to the production of other part type follow. The control is decentralized and robust. The perturbances are eliminated by the auxiliary buffers. So, the above statement is valid until these buffers allow. The best feature of the use of this approach is the extremely simple work organization.

4.7 Discussion

Considering the advantages of this approach the following can be emphasized. In batch processing environment it is very difficult to utilize the enormous advantages of series division and overlapping production.

Complicated schedules should be developed, sometimes with difficulties in the organization of realization. In HDS automatic scheduling is realized. Automatic series division and overlapping production is performed. The part type processing on machine groups are made significantly independent. At batch processing, the part type pieces processing is unnecessarily ordered. At the use of HDS this ordering is flexible and the processes "organize themselves" to be effective.

Let us remind one more point. Batch processing scheduling is not very suitable when machine tools with adaptive control are used. HDS is very much suitable for this case.

At batch processing the scheduling becomes a combinatory problem. Only full enumeration can guarantee finding the best solution. But this way for most of the problems is not suitable because of the enormous dimension of search space. Heuristic and 1other optimization methods can give suitable solutions. But, in other cases the solutions can be very far from to be satisfactory. Different approaches are available to improve the schedules. One, very effective, is the series division and overlapping production. But, as far as we know, not standard approach to the use of this is available. The solutions obtained using heuristic methods is difficult to realize. A lot of administration, organization is involved in that. Exactly opposite is the situation at the use of HDS. Only the demand rates should be computed. The demand rates determination method proposed by us reflects the technological and processing capacity constrains together. The series division is performed automatically by periodic motions. Overlapping production is involved in the system processes. The only open problem is the organization of fill-up of auxiliary buffers. It seems to us that this problem might have very effective solution depending on production situation (order of manufacturing sequences, etc.).

SUMMARY

The definition of control is "Organization of goal oriented actions". Usually, control is understood as organization of dynamic processes. In modern manufacturing the processes are mostly realized by devices using feedback control systems (CNC machine tools, robots). These work in large scale system environment. The sub-system interact in complex way in integrated manner. The material and information processes are organized into process and cost effective system. To open new horizons for the increase of effectiveness and competitiveness new features should be opened. In present paper some important topics for performing this goal is discussed.

The optimization of cutting process is one problem which is the closest to the realization. Understanding and effective solution of these problems has basic effect on the overall system performance. Development of the idea leads to new features (technological data bases, adaptive control, primary and secondary optimization, learning systems, etc.).

Close connection exists among process and motion planning problems. The parametric method and optimal trajectory planning open effective and universal way to solve the optimal input signal planning problem for robots. But as well for 3D, 4D, 5D manufacturing problems. In realizing the motions advanced control methods (computed torque method, model reference adaptive control, etc.) may be used for high extent.

Finally, the present paper shows that one of the most important problems, the scheduling of process (to determine which process, in which device, when will be performed) can be solved, very effectively, using dynamical method instead of classical operation research approaches.

Of course, the control problems of manufacturing are much wider than it could even be reviewed in such a summarizing paper. But, we hope that the more is known the better the world can become. Might be, this paper helps to know a little bit more.

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