TECHNICAL UNIVERSITY IN LIBEREC
Faculty of Mechanical Engineering

DIPLOMA PROJECT

DESIGN OF THE SERVODRIVES FOR THE TOOL MANIPULATOR

Liberec 1995

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TECHNICAL UNIVERSITY IN LIBEREC

FACULTY OF MECHANICAL ENGINEERING

DEPARTMENT OF MANUFACTURING SYSTEMS

DESIGN OF THE SERVODRIVES FOR THE TOOL MANIPULATOR

DIPLOMA PROJECT

Study discipline: (23-19-8) Manufacturing Systems

DMS No. 68

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Consultant:

Extent of the Diploma Project

Number of pages: 58

Number of Figures: 19

Number of tabulate: 5

Technical University in Liberec

Faculty of Mechanical Engineering

Department : Manufacturing Systems **School Year :** 1994/1995

DIPLOMA PROJECT

Graduate : Hossam NABHANI

Study discipline : (23-19-8) Manufacturing Systems

According to the Law Digest No. 172/1990 for the Universities, the Head of the Department of Manufacturing Systems Determines you this Following Topic for your Diploma Project :

PROJECT HEADDING : Design of the Servodrives for the Tool Manipulator.

CONTENT ITEMS :

1. Introduction.
2. State of the Art in the Tool Management for FMS.
3. Description of the Tool Manipulator for FMS and its Function.
4. Time Analysis for Tool Transport:
   - from Storage to the Automatic Tool Changer
   - from Storage to the Transporting Carriage
   - whitin the Storage
5. Design of the Servodrives for the Tool Manipulator Axis X and Y. Maximum Average Time for the Transport from Storage to the Automatic Tool Changer and Back: $T_{max} = 30$ sec.

   Other parameters:

   Total Accuracy of Positioning .... 0,1 mm
   Mass of the X Axis .... 830 kg
   Mass of the Y Axis (30 kg Tool Included) .... 250 kg
   Mass of the Balance Weight of the Y Axis .... 220 kg
   Minimum Position Gain .... $Kv = 5\ sec^{-1}$
   Total Number of Tools 144
6. Examples of Manipulator Utilization.
7. Conclusions.

Drawings :

Text : 40 pages (figures including)

References :

/1/ HARTLEY, John: FMS at Work. IFS (Publications), UK, 1984

/2/ Description of the Tool Manipulator for PVS 400 (FMS in TOS Olomouc)

/3/ All Digital AC Servodrives for Speed Control. Yaskawa, Japan, 1993

Supervisor : Ing. Jan Skalla, CSc.

Consultant :

Begining Date : 31.10. 1994

Submission Deadline : 26.5. 1995

Semester : Summer

TECHNICKÁ UNIVERZITA V LIBERCI -7-

Doc. Ing. Přemysl Pokorný, CSc.
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Dean

Liberec 31.10. 1994

Declaration

I declare that I developed my diploma project independently with aid of referred literature under the control of supervisor and consultant.

In Liberec, 20. 5. 1995

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Signature

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The used symbols

a .... acceleration [$m.s^{-2}$]

D .... diameter of rolling pinion [m]

F_T .... passive force [N]

g = ... gravity acceleration [$m.s^{-2}$]

i .... gearing ratio

i_c .... total gearing ratio

I .... moment of inertia [$kg.m^2$]

I_{TOT} ..... total moment of inertia [$kg.m^2$]

I_m .... inertia of motor [$kg.m^2$]

I_{gear} .... inertia of gear box [$kg.m^2$]

I_{ret} ..... reflected moment of inertia [$kg.m^2$]

n_m .... number of revolution of motor [r/min]

m .... mass [kg]

v .... velocity [m/s]

ϵ .... angular accelaration [rad/s^2]

r .... module

t .... time [s]

t_a .... time for accelaration [s]

t_d .... time for decclaration [s]

t_r .... time for ramping acc/decc [s]

t_c .... time for complete exchange [s]

X .... distance of X axis [m]

X_k .... sum of ditances from point k

Y .... distance of Y axis [m]

T .... torque [N.m]

T_a .... torque at acceleration [N.m]

T_d .... torque at deceleration [N.m]

T_{max1} .... preliminary value of torque for selection of the motor [N.m]

T_p .... passive torque [N.m]

T_u .... torque unbalancing[N.m]

T_{eq} ...... torque equivalent[N.m]

T_{nom} ..... torque nominal[N.m]

T_{tot} ..... total torque [N.m]

ATC ...... Automatic Tool Changing

APC ...... Automatic Pallet Changing

AGV ...... Automatic Guided Vehicle

CNC ...... Computer Numerical Control

CCM ...... Citoen Construction Mechaniques

FMS ...... Flexible Manufacturing System

1. INTRODUCTION

A unique opportunity of increasing profits and return on capital is waiting for companies ready to involve themselves comprehensively in FMS (flexible manufacturing systems).

And with FMS it is practical to combine high productivity with small batch sizes and short lead times. With FMS, it is possible to machine two or three different engine cylinder blocks, or valve and pump bodies, in low volume at relatively low cost.

And now we may ask what is FMS ? When Williamson, director of R and D at Molins, Deptford, London, invented the concept, he was thinking in terms of a flexible machining system, and it was in machine shops that the first FMS was installed. His concept was called "system 24" because it was intended to operate for 24 h a day, under the control of a computer, but otherwise unmanned, on the 16-h night shift. That was the beginning of the path to FMS.

And we can EXCEPT from FMS:

1- reduced plan size,

2-increased machine utilisation, which with (1) and (3) reduce over heads,

3- work-in-progress reduced by at least half,

4- unmanned operation reducing labor costs,

5- reduced setting-up time,

6- quicker model change,

7- shorter delivery times,

8- consistent accuracy,

9- standardisation of techniques,

10- longer life of capital equipment.

And now we can say, that all manufacturing flexible machines cells and systems need some sort of automatic tool management. It means that every machine in the system has an automatic tool magazin which gives possibility for changing the tool according to the programme requirements. In fliexible machining system (PVS 400) in (Tos Olomouc), the tool manipulator is using an old D.C drive Mezomatic. The aim of my project is to design and select a modern AC servo drives for this tool manipulator.

2. STATE OF THE ART IN THE TOOL MANIPULATORS FOR FMS

The management of tools in an FMS is just as critical as the management of the flow of work pieces. With an FMS of ten machine tools, there may be 3,000-5,000 tools in the system. If there are shortage, or tools keep breaking, the plant will spend a lot of time idle, as machines wait for tools to be renewed. Then, the utilisation will be lower than expected, so the advantage of unmanned operation will be negated. In some cases, it has been found that the flow of tools through the shop caused more problems than the flow of work pieces, and in many others, the engineers have failed to solve the problems of handling the tools. Instead they have abandoned the concept of unmanned operation because they decided that the manned changing of tools was either necessary or preferable. It is true that automatic tool changing between the ATC and the stores can be a complicated business, but if the manual tool changing is allowed to prevent unmanned operation, then the engineers have failed, the reason is simply that because FMS are capital intensive, they need to be operated for 16-24 a day to give a good return on capital so that the company can be competitive.

Since as FMS of five machines may be able to do the work of 15-20 conventional machine tools, it must be able to operate with less tools than are needed in a conventional machine shop when the FMS is built around a group of CNC machines. In one company with the introduction of an

FMS, the number of tools was reduced from 600 to 63 and in another from 700 to 73 standard tools, with only 16 special tools, quite rightly, planners will baulk at the idea of investigating the thousands of tools needed in the system before each job is planned. To avoid such long and tedious process, some from a computer program is essential. The starting point is a data base. The essential data includes the tool number, the machines in which it can be used, the tool wear situation, the tool size, there are ISO standards for coding inserts, for cutting tools, for example and these can be used as the basis of identification (Fig. 1).

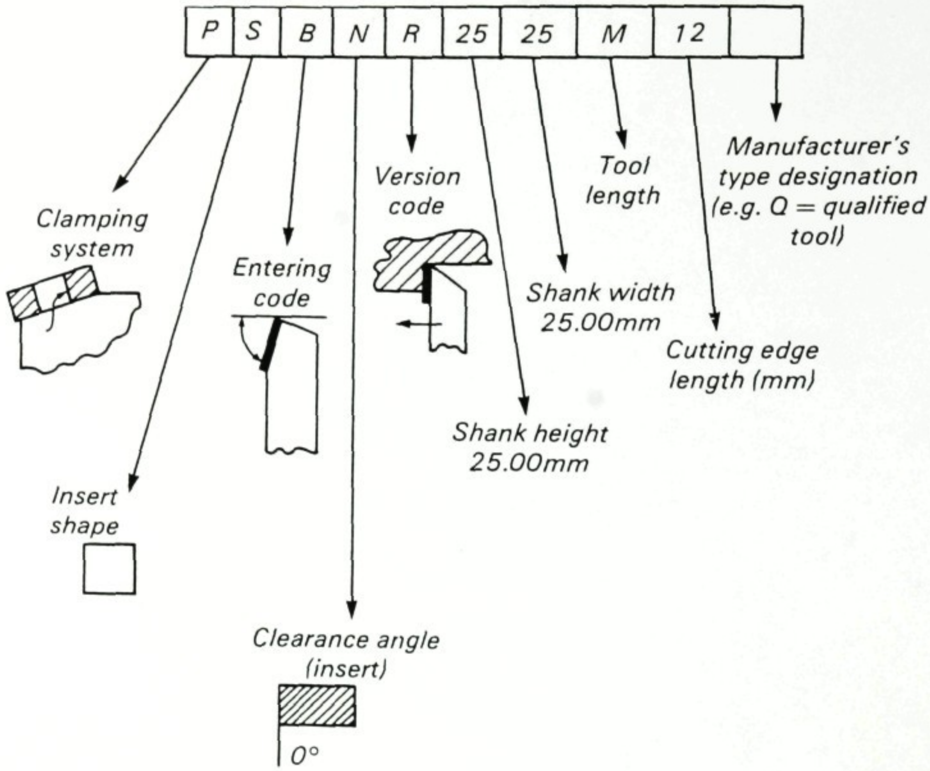

Fig. 1. ISO codes for turning tool inserts are a good start for a tooling data base

Machining centres are available with from 20 to 60 tools, but some are equipped with 90 tools. Even 90 tools is unlikely to be enough in most cases, so if some tools are to be changed manually at the ATCs, then it is better to specify the largest units available. However, if tool changing between the ATCs and the stores is automated, smaller ATCs may suffice (Fig. 2).

However, to obtain maximum utilisation of equipment, it is better to try to use AGVs as tool changers. For example, even in a system of 10-12 machines, one AGV may be adequate in theory, but it is preferable to install two so that any break downs do not cause major stoppages, and to allow on-board changing. In that case, it makes sense to use the second AGV to transport tools, and in a very small system, one AGV can do both jobs and still some time over.

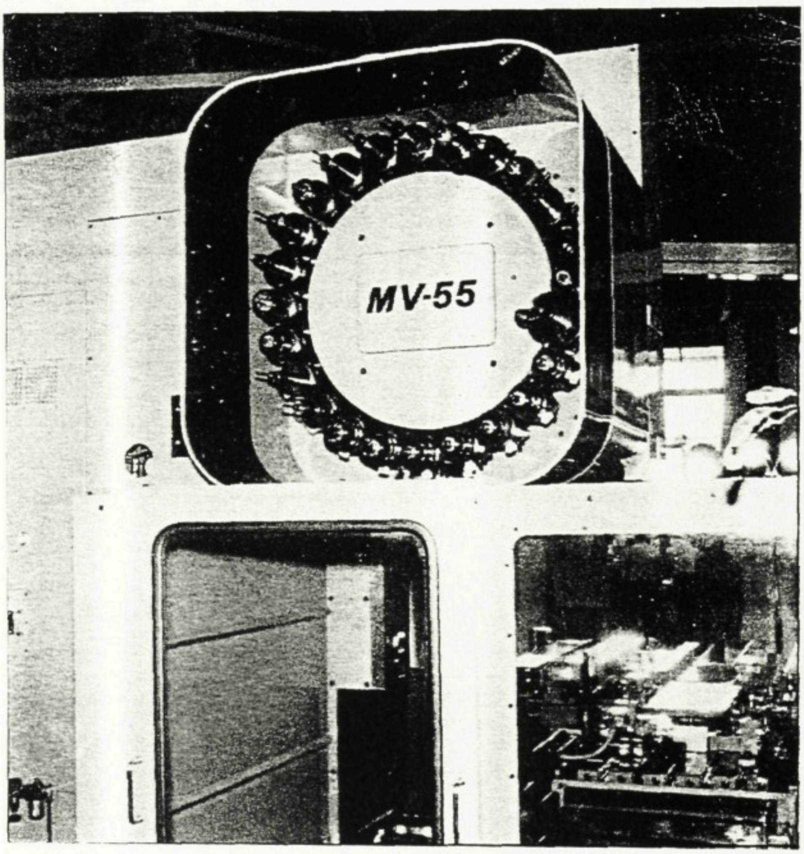

Fig. 2. Large ATCs are prefreable on machining centres

In the semi-manual approach to tool handling, an operator selects tools, in response to data supplied by the control computers, and makes them up into a set at a transport station. Then, the AGV comes to collect the tools and takes them to the machining centre. In the Okuma FMS, for example there are seven stations in the tool room including a tool picking area, a presetter and a grinder.

At the tool stations, new tools are prepared and preset from the store of 500 tools (Fig. 3). The new set of tools and their carrier are transferred by AGV - There is only one in the Okuma FMS - to a table along side the machining centre. Tools are changed manually when the batch changes, or when the tools have worn to their limit. However, the operation of the shop should be such that tools are changed in the manned shifts only, as they are in this case.

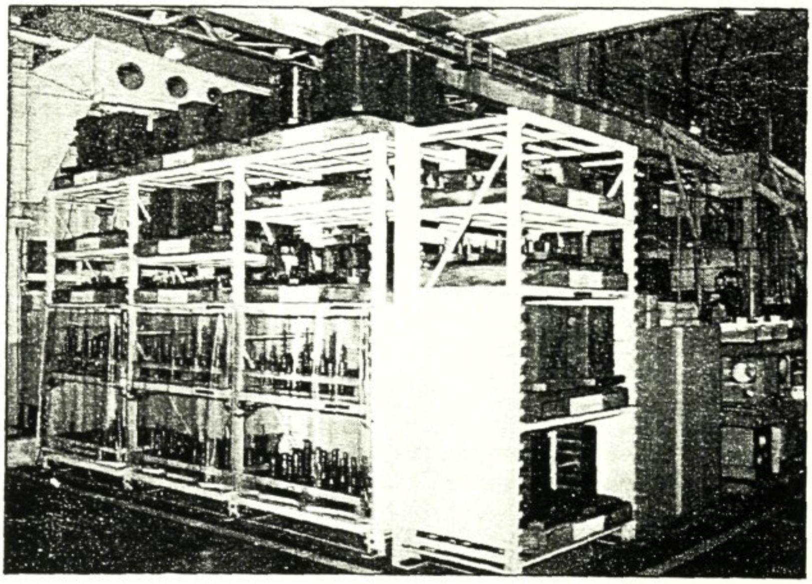

Fig. 3. A small manually accessed tool and fixture stores for an FMS with seven machining centres

Other companies have devised small tool racks or special fixtures able to carry five or ten tools, the assembly being mounted on a pallet for transfer between the tool stores and the APC. The tool carrier is moved to the work-table so that the tools can be transferred via the spindle to the ATC. this system should only be used where cycles are very long, because it goes against one of the principles of FMS to keep that spindle cutting metal for as high a proportion of the time is practical.

Tools are changed automatically in FMS at Citroen construction Mechaniques (CCM) and at Yamazaki machinery. At CCM, there are two machining centres, with space for a third. These are equipped with ATCs carrying 50 tools, and are backed up by a central store with space for 600 tools. There is a tool handling device at the tool stores, another at each machine, and an AGV in the system.

Since the operations can be performed while the machining centre is cutting metal, as they can on some Cincinnati Milarcon and Toyoda machining centre. This is an excellent way to automating tool transport.

However, it does involve extra investment in the drums and pick-and-place arms. With a large system, the use of one pick-and-place arm at each machine would be expensive. In Italy, jobs spa-has developed two-tier tools carrying AGVs, and a Cartesian coordinate robot at the machine to change tools. The trolley can carry about 40 tools mounted vertically on circular racks, but as in the Grafenstaden system used by CCM, a robot is needed at each machine, although in the jobs system, the robot can be a simple device built on to the side of the machine.

Alternatively, a system could be built around vertical racks in which the tools are mounted horizontally, And on AGV/robot. To speed up loading, the tool stores could be a carousel type, the rack moving around as necessary to present the correct tool at the loading station. The AGV would also have racks or drum in which the tool were carried horizontally. The robot would be a simple arm pivoting at one end of the AGV on a horizontal axis with about 75° movement each side of the vertical, it would also have a horizontal pivot halfway along, and the tool gripper would be able to move horizontally.

The rack of tools on the AGV can be designed to carry from 10 to 15 tools. The AGV would draw up along side the stores, and the arm would articulate so that it over hangs the end of the AGV to pick tools from the stores. Once these has been loaded, the AGV would move to the machining centre, and exchange worn tools for new ones. Since the robot arm would have only three axes of freedom, it would be simple, yet it would be able to reach tools in a large drum or in a large rack if necessary. It could be built on a simple lift to reach the ATCs on large machining centres, but normally the ATC would revolve to present the tools in sequence to the robot (Fig. 4).

In its FMS, Yamazaki transfer the ATC drums themselves between the machines and the stores. As a result, very many tools can be used. In

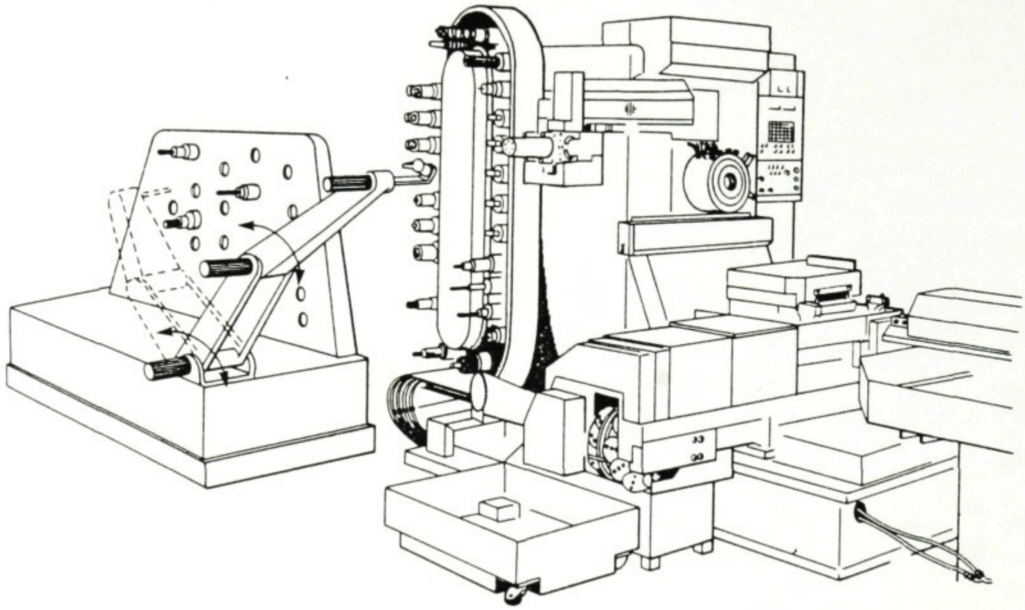

Fig. 4. Concept of simple AGV/robot for tool changing

the first MFS, two tool drums are mounted back-to-back on columns behind the machines.

The drums can be slid along the machine for use. And when necessary, the complete drum/column assembly is transferred to the tool room by a gantry crane. That system has some draw backs, such as the need to move the complete columns to the tools stores, where they occupied a lot of space. Also the gantry crane is not an inherently precise piece of equipment and moves slowly (Fig. 5).

Each machine in the frame and box line has a 40-tool ATC, but in this case the drums themselves are detachable. There is one drum in use on the machine, and another is on a horizontal slide that extends along the side

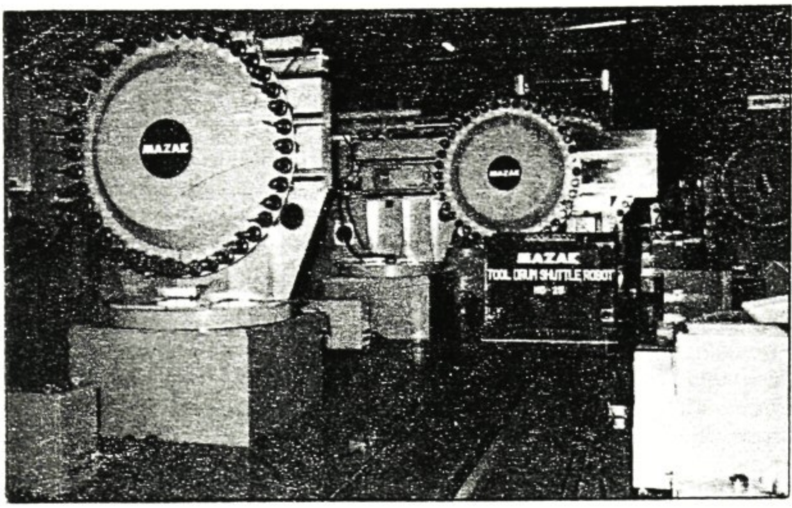

Fig. 5. Yamazaki uses a rail-guided AVG to transport tools between the stores and machining centres

of the machine, between the two lines of machines is a track for a rail-guided AGV, which has a structure similar to that on the machine with a horizontal slide mechanism on each side. Therefore, the drums can be slide from the machine on to the AGV, which then transfer them to and from the tools stores as necessary. The AGV carry two drums at the same time in the two lines, there are 19 machines, and in all, 34 drum in use.

In the tool room the operator uses a Sony instrument to measure the tools, which are regrind or renewed as necessary. Before a tool is used again, the offset is measured and is fed to the control computer in preparation for use on any machine. Then the operator loads the tools on to the drums (Fig. 6).

In fact, this is one area where theory and practice have not agreed.

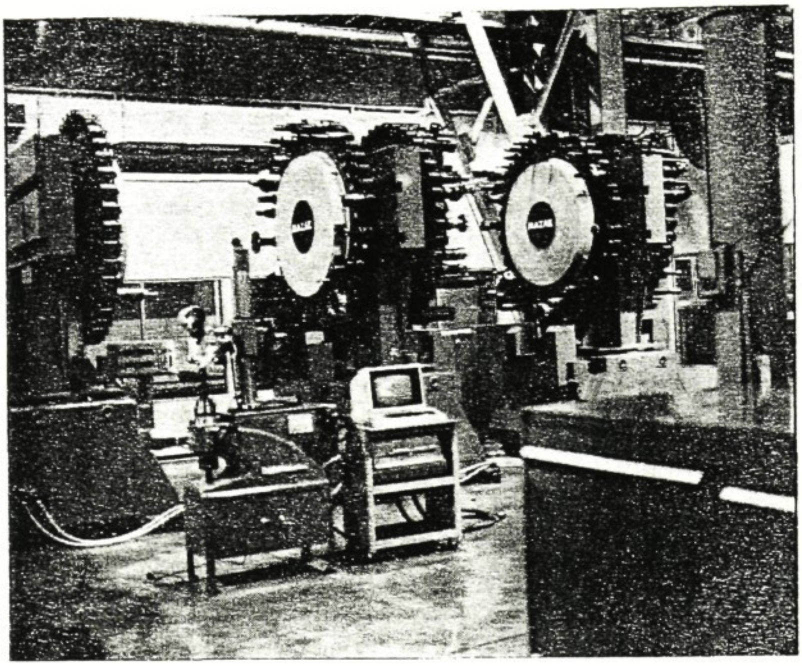

Fig. 6. Tools being prepared for use in Yamazaki tool room

The problem involved the tolerance on the tools, drum and machines. In theory, it should be possible to measure the offset of the tool in the tool room, and feed the data in the computer so that when the tools are transferred to any drum on any machine, a correct offset data is sent as well. However it was found that there were discrepancies between the actual dimensions and the measured offsets. Therefore, data were collated from each drum and for each machine to compensate for vibrations. It is now possible to use any tool on machine without any manual checking. That exercise indicates how many problems there are to be solved in FMS.

Over all, though, the Yamazaki tool changing system is expensive and has the draw back of limiting the user to one make of machining centre, obviously that is not a problem for Yamazaki but it could be for a potential customer. In addition, as the problem with the offsets shows, it is prone to errors. Therefore, tool changing based on the concept of an AGV/robot seems a more economical solution.

Even so, before the offset problem was solved, the FMS was working adequately, with a low level of manning and with automated tool changing.

So long as the plant is designed with automated tool changing in mind, minor teething troubles will not prevent it from operating unmanned some of the time. Of course, if no attempt is made to solve the tool handling problem, it will always be difficult, if not impossible, to operate unmanned.

3. DESCRIPTION FOR TOOL MANIPULATOR FOR FMS AND ITS FUNCTION

There are two functions:

A- Tool casing is gripped by manipulator and transported to the exchange station. Then, exchange station going forth to be in one plane with spindle and waiting for exchanging operation. After finishing machining with old tool the spindle stops at a position for exchanging and is going at the same level with exchange station, then exchange arm start to operate for changing the tools. Spindle starts machining with new tool and exchange station with old tool is going back and stay part of the magazine so the manipulator gripes the old tool and transport it into the magazine.

B- Transferring the tools to and from the tool shop. The manipulator gripes the tool and transport it on the carriage. The carriage then transports the tool to the tool shop at a velocity 120 m/min to the same magazine like at the machine. And the manipulator in the shop transports the tool from the carriage to the magazine. For the break down situation, it is possible to use manual input when tools are transported by manual carriage to the magazine, see (Fig. 7). The parts are:

1- casing

2- tool

3- code identification

4- horizontal carriage with tool gripper

5- manual carriage

6- column

7- vertical carriage

8- carriage for transporting tools from the tool shop

9- magazine

10- exchange station

11- exchange arm

12- spindle

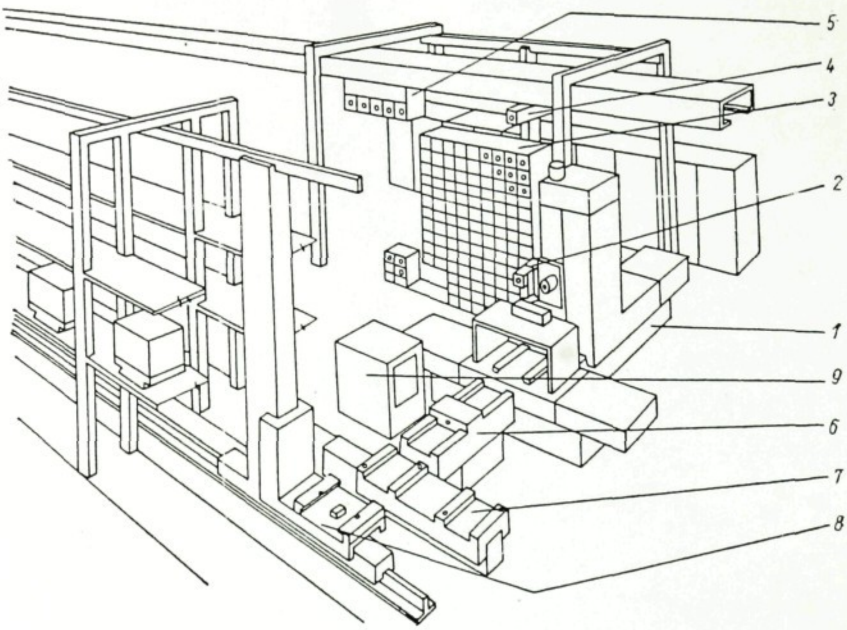

Fig. 8. Description of tool manipulator for FMS and its function

(Fig. 8) is a description of the tool manipulator for FMS and its function.

1- milling centre

2- exchange station

3- magazine

4- tool manipulator

5- carriage for transport from and to the tool shop

6- pallet exchanger

7- sliding table

8- pallet manipulator

9- washing machine

4. TEMPORAL ANALYSIS OF THE PROBLEM

Solving the problem from technological side for machining centre to produce work pieces with dimension of 400.400 mm, it was deduced that the manipulator must be able to transport the old tool to magazine, looking for new tool and prepare it for exchange station in 30 seconds but before knowing the conditions which must be afforeded in the manipulator, we should recognize the working area when the manipulator takes it.

The manipulator stops only in deposition places for the tools, and its movement is by steps multiplied of 210 mm in x axis and 170 mm in y axis. All machinery equipment which operated, by the manipulator as exchange station, the carriage between the manual guided vehicle and machining centre, are located in existing positions which must be away from each other, the distance multiply of 210 in x axis or 170 in y axis (Fig. 9).

TIME ANALYSIS FOR TOOL TRANSPORT

4.1. Average distance of manipulation with in magazine

We will execute first of all on the simplified sample demonstrated on the Fig. 10.

We speculate about movement in one axis and four places for putting of tools. Probability of the presence of manipulator is for all points the same, (points 0-3 Fig.10).

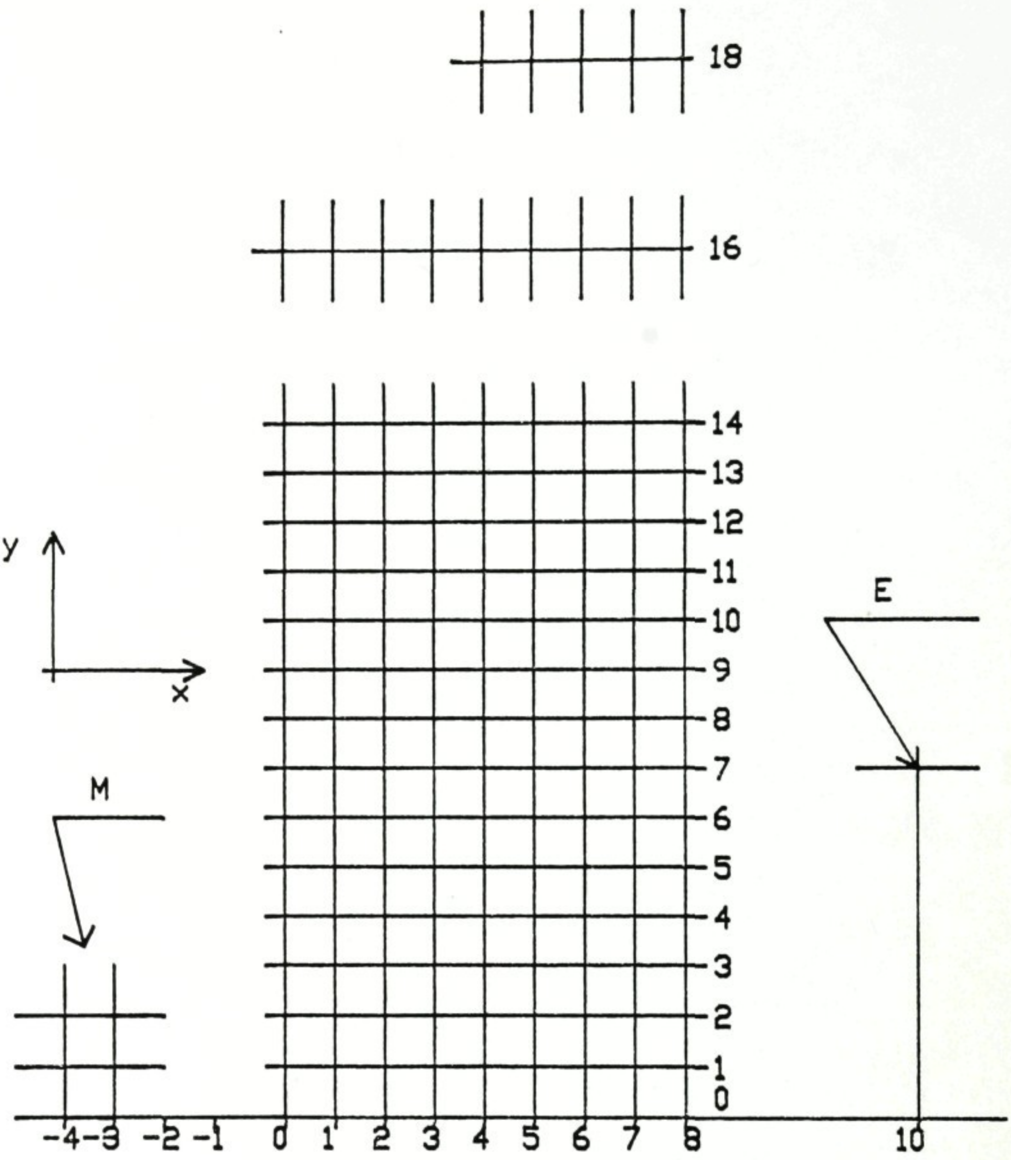

Fig. 9. Tools magazine

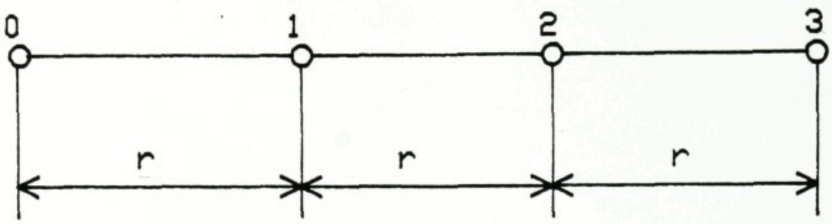

Fig. 10. Scheme for calculation of the average ditance

From the starting point manipulator can go to all other points, and the probability is for all points the same again. The average distance of the manipulator movment is then the sum of distances between all points divided on the number of those distances. For sample on the (Fig.10) will be total sumation of distances from a single points.

$$\begin{aligned} x_0 &= r(1+2+3) = 6r \\ x_1 &= r(1+1+2) = 4r \\ x_2 &= r(2+1+1) = 4r \\ x_3 &= r(3+2+1) = 6r \end{aligned} \tag{1}$$

Total sumation

$$\sum_{k=0}^{3} x_k = r(6+4+4+6) = 20r \tag{2}$$

Total number of distances summated

$$m = 3.4 = 12 \tag{3}$$

Average distance between points 0-3 is

$$x_{average} = \frac{\sum_{k=0}^{3} x_k}{m} = \frac{20r}{12} = 1.67r \tag{4}$$

In general cause for n points , the sum of distances from each single point is

$$\begin{aligned}
x_0 &= r[1+2+3+...+(n-1)+n] = \frac{n+1}{2}n \\
x_1 &= r[1+1+2+...+(n-2)+(n-1)] = 1+\frac{(n-1)+1}{2}(n-1) \\
x_2 &= r[2+1+1+...+(n-3)+(n-2)] = 1+2+\frac{(n-2)+1}{2}(n-2) \\
&\vdots \\
x_k &= r[k+(k+1)+...+2+1+1+2+...+(n-k-1)+(n-k)] = \\
&= r[\frac{k+1}{2}k+\frac{n-k+1}{2}(n-k)] \\
&\vdots \\
x_n &= r[n+(n-1)+...+2+1] = r[\frac{n+1}{2}.n]
\end{aligned} \tag{5}$$

By rearrangement of the equation

for x_k we obtain:

$$x_k = (k^2-n.k+\frac{n^2+n}{2})r \tag{6}$$

There is a relation we can write for the sum

$$\sum_{k=0}^{n} X_k = [(n+1)\frac{n^2+n}{2}+\sum_{k=0}^{n} k^2-n\sum_{k=0}^{n} k]\, r \qquad (7)$$

because its valid

$$\sum_{k=0}^{n} k^2 = \sum_{k=1}^{n} k^2 = \frac{n(n+1)(2n+1)}{6} \qquad (8)$$

$$n\sum_{k=0}^{n} k = n\sum_{k=1}^{n} k = \frac{n(n+1)}{2}.n \qquad (9)$$

Then we can deduce after rearrangement the equation

$$\sum_{k=0}^{n} X_k = \frac{n^3+3n^2+2n}{3}.r \qquad (10)$$

For the number of members which are considered in the sum (10) is valid (see relations 5)

$$m = n(n+1) \qquad (11)$$

The average distance is given by ratio

$$X_{aver} = \frac{\sum_{k=0}^{0} X_k}{m} = r\frac{n^3+3n^2+2n}{3n(n+1)} = r\frac{n^2+3n+2}{3(n+1)} \tag{12}$$

The scheme for store of tool manipulator is on (Fig.9)

and the store has 19 rows and 15 columns (module in horizontal direction 210 mm, in vertical direction 170 mm). The rack of tools has the bounders given by row 0 and 16 and column 0 and 8 and row number 18 its carriage for transporting between machines and tool shop. The manual carriage for exchanging the tools manually is in columns -3 and -4 Considering the manipulator is travelling at the tool rack, it means in the area limited by row 0 and 16 and column 0 and 8 the average distance according to equation (12) for axis x (n = 8) will be:

$$x_{aver} = r_x . \frac{n^2+3n+2}{3(n+1)} = 3.33 . r_x = 700 \ mm \tag{13}$$

and for y axis (n = 16)

$$y_{aver} = r_y . \frac{n^2+3n+2}{3(n+1)} = 6 . r_y = 1020 \ mm \tag{14}$$

The maximum travel then

$$x_{\max} = r_x . n = 210.8 = 1680 \ mm \tag{15}$$

$$y_{max} = r_y . n = 170.16 = 2720 \; mm \qquad (16)$$

4.2. Average distance from magazine to exchange station (Fig. 9).

Manual carriage M and carriage for the transporting the tools to the tool shop (row 18) are not used in the normal operation. The sum of distances between exchange station and the tool magazine will be for x-axis

$$\sum_{i=0}^{8} x_i = r_x [10+9+8+.......+3+2] = \\ = r_x . \frac{10+2}{9} . 9 = 54 . r_x \qquad (17)$$

Average distance in x axis will be

$$x_{aver} = \frac{\sum_{i=0}^{8} x_i}{m_x} = 54 . \frac{r_x}{9} = 1260 \; mm \qquad (18)$$

And the same for axis y will be

$$\sum_{i=0}^{16} yi = r_y [7+6+....+2+1+1+2+...+6+7+9] = \\ = r_y [(7+1).7+9] = 65 . r_y \qquad (19)$$

$$y_{aver}=\frac{\sum_{i=0}^{16} y_i}{m_y}=65\,.\,\frac{r_y}{15}=740\ mm \qquad (20)$$

The longest travelling length in axis x during exchange of tool will be (n=10)

$$x_{max}=r_x\,.\,n=210\,.\,10=2100\ mm \qquad (21)$$

and in axis y (n=9)

$$y_{max}=r_y\,.\,n=170\,.\,9=1530\ mm \qquad (22)$$

4.3. Average distance manipulation during loading and unloading

The sum of all possible distances in y axis will be

$$\sum_{i=0}^{15} y_i=r_y[18+17+...+5+4+2]=$$
$$=r_y[\frac{18+4}{2}\,.\,15+2]=167\,.\,r_y \qquad (23)$$

average distance

$$y_{aver}=\frac{\sum_{i=0}^{15} y_i}{m}=\frac{167\,.\,170}{16}=1770\ mm \qquad (24)$$

During calculation the average distance in x axis is necessary to work out from analogical relation (5) Total sum (7) will not be over n elements but over l element (l=0 to 4-number of places in carriage). We will overwrite expression (7) for 1 element:

Transport from carriage to magazine (Fig. 9).

$$4:\ x_4=r_x(4+3+2+1+1+2+3+4)=20.r_x$$

$$3:\ x_3=r_x(5+4+3+2+1+1+2+3)=21.r_x$$

$$2:\ x_2=r_x(6+5+4+3+2+1+1+2)=24.r_x$$

$$1:\ x_1=r_x(7+6+5+4+3+2+1+1)=29.r_x$$

$$0:\ x_0=r_x(8+7+6+5+4+3+2+1)=36.r_x$$

The $\sum$ *of arithmetical series is*

$$\sum_{a=1}^{n} a=\frac{n+1}{2}.n=\frac{9.8}{2}=36$$

General equation for the all possible movements in the axis x is (see also eguation(7)):

$$\sum_{k=0}^{l} x_k=r_x[(l+1).\frac{n^2+n}{2}+\sum_{k=0}^{l} k^2-n\sum_{k=0}^{l} k] \qquad (25)$$

Using equations (8) and (9) and set up we obtain

$$\sum_{k=0}^{l} x_k=r_x[\frac{(l+1).(n^2+n)}{2}+\frac{2l^3+3l^2+l}{6}-n\frac{l^2+l}{2}] \qquad (26)$$

The sum number of elements (26) is

$$m=n(l+1) \qquad (27)$$

For rack according to (Fig. 9) will be average distance during loading and unloading from carriage transporting between working places and the tool shop.

(l = 4, n = 8)

$$x_{aver}=\frac{\sum_{k=0}^{l} x_k}{m}=\frac{r_x.130}{40}=680\ mm \qquad (28)$$

Maximum distance during loading and unloading carriage is

$$x_{max}=r_x.n=210.8=1680\ mm \qquad (29)$$

$$y_{max}=r_y.n=170.18=3060\ mm \qquad (30)$$

The result or out come is explained in table 1.

Table 1. Average and maximum distances of manipulation.

	[mm]	Manipulator within magazine	Magazine exchange station	magazine carriage
x	average	700	1260	680
	max	1680	2100	1680
y	average	1020	740	1770
	max	2720	1530	3060

4.4. Travelling time for ramp acceleration and decceleration

Deriving of ramping acceleration and decceleration is very advantageous from point of view weight of drive in (constant acceleration) and from point of view we get high average velocity.

Average velocity travel

At the both coordinates (x,y) manipulators during their work are not limited at all, and the time for displacement is equal to time for travel and acceleration. In general ramping function (Fig. 11), it means with constant acceleration for travel distance this equation is valid.

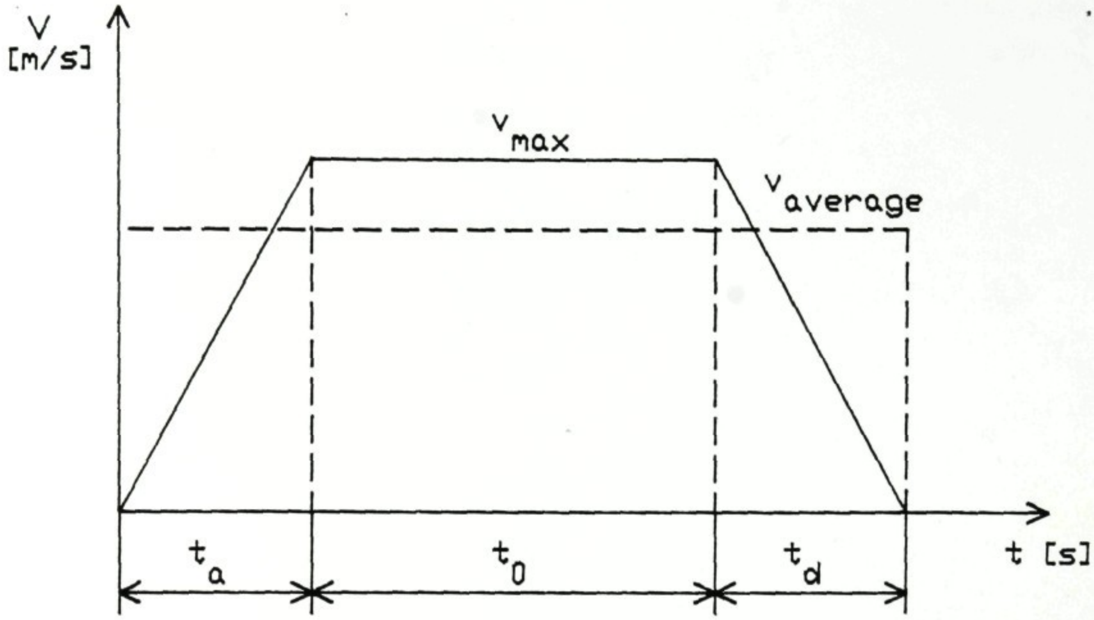

Fig. 11. course of the velocity for $X > X_{lim}$

$$x = v_{max} \left(\frac{t_a}{2} + t_0 + \frac{t_a}{2} \right) \tag{31}$$

t_0 is time of going on constant velocity (Fig. 11) and because acceleration and decceleration of drive has the same magnitude, is valid.

$$t_a = t_d \tag{32}$$

And here after substituing in (31)

$$x = v_{max} (t_0 + t_d) \tag{33}$$

Average velocity gives ratio of travel distance to total time

$$v_{aver}=\frac{x}{t_a+t_0+t_d}=v_{\max}\frac{t_0+t_a}{t_0+2t_a} \qquad (34)$$

from expression (33) we can express

$$t_0=\frac{x}{v_{\max}}-t_a \qquad (35)$$

And substitute to (34) after adjustment we will get equation for magnitude of average velocity.

$$v_{aver}=\frac{x}{\frac{x}{v_{\max}}+t_a} \qquad (36)$$

which is valid only for size of distance x, when drive start running in full speed. If path x is shorter, drive before getting the maximum speed will start decceleration and time course of speed will have shape like in (Fig. 12) average velocity is not possible to derive from relation (34), but is valid for it

$$v_{aver}=\frac{x}{t_{a1}+t_{d1}}=\frac{x}{2t_{a1}} \qquad (37)$$

when x $\leq$ x limit (Fig. 12) drive decelerate immediately after acceleration

$$t_{a1}=t_{d1} \qquad (38)$$

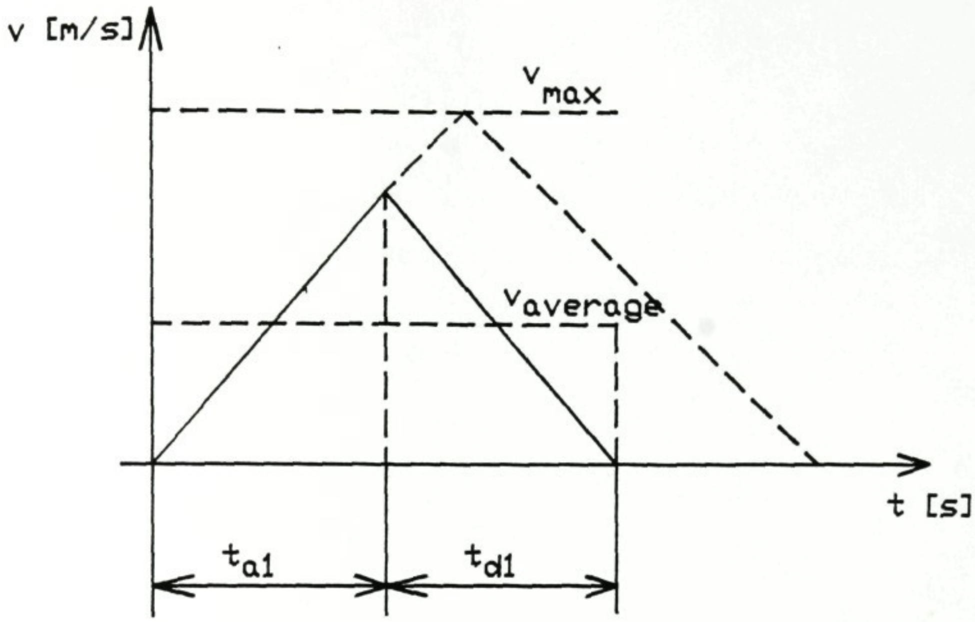

Fig. 12. Course of the velocity for $X \leq X_{lim}$

X limit is possible to determine if is valid relation (36) or (37) in the distance.

$$x_{lim}=2\left(\frac{1}{2}a.t_a^2\right)=a.t_a^2 \qquad (39)$$

we can substitute v = a.t

$$t_a=\frac{V_{max}}{a} \qquad (40)$$

and then for the given data

$$x_{1im}=\frac{v_{\max}^2}{a}=\frac{1^2[m/s]^2}{1m/s^2}=1m \qquad (41)$$

To relation (36) we can substitute (40) and to relation (37)

$$t_{a1}=\sqrt{\frac{x}{a}}$$

$$v_{aver}=\frac{x}{2t_{a1}} \ , \ t_{a1}=\sqrt{\frac{x}{a}} \ , \ x=a.t_{a1}^2 \qquad (42)$$

$$v_{aver}=\frac{1}{2}x\sqrt{\frac{a}{x}}=\frac{1}{2}\sqrt{a.x}$$

after arrangement will get relations for average velocity travel

$$v_{aver}=\frac{v_{\max}}{\frac{v_{\max}^2}{a.x}+1} \quad for \ x\geq x_{1im} \qquad (43)$$

$$v_{aver}=\frac{1}{2}.\sqrt{a.x} \quad for \ x\leq x_{1im} \qquad (44)$$

The last relation illustrates the known actual, that average velocity during movement $x \leq x_{lim}$ is independent on size of maximum velocity of drive see (Fig. 12). Relations (43) and (44) is possible to ameliorate to better form:

$$\frac{v_{aver}}{v_{max}} = \frac{1}{\frac{x_{lim}}{x}+1} \quad for\ x \leq x_{lim} \tag{45}$$

$$\frac{v_{aver}}{v_{max}} = \frac{1}{2} \cdot \sqrt{\frac{x}{x_{lim}}} \quad for\ x \leq x_{lim} \tag{46}$$

Relations (43) and (44) for depending the average velocity on speed v_{max}. Are graphically represented in (Fig. 13).

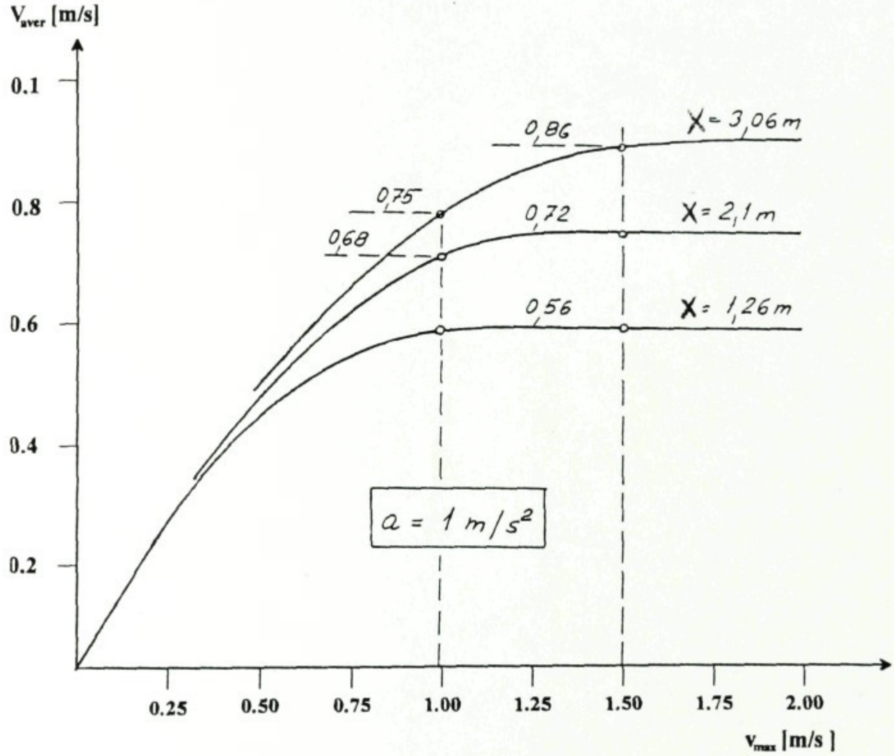

Fig. 13. Relation between $v_{average}$ and v_{max} for ramp acceleration and deceleration

Acceleration is $a = 1\ m/s^2$ dependence the average velocity on v_{max} are plotted for paths determinating changing time. It means 1260 and 2100 mm and for longest possible path 3060 mm (see tab. 1). (Fig. 13) shows that will be good to choose transport speed v_{max} = 1 m/s (60 m/min). For the higher max speed (1,5 m/s) over path 1,26 m average velocity will not be higher. For the path 2,1 or 3,06 m average velocity increase for 15 or 5,9% only.

Time for transport

Manipulator axis works independently so the time for transport is given by axis which goes longer path (in table .1 it is marked with thicker lines) Time for transport is given by the path and average velocity according to

$$t=\frac{x}{v_{aver}} \qquad (47)$$

Average velocity is given by relation (43) (44) if we decide for the max velocity

v_{max} = 1 m/s = 60 m/min

It gives according (41)

$$x_{lim}=\frac{v_{max}^2}{a}=1\ m$$

For all situation which we will consider is valid equation (43), because the all travelling distances are greater than x_{lim} if we take (43) to (47) we obtain

$$t=\frac{x}{v_{max}}\left(1+\frac{v_{max}^2}{a.x}\right) \quad x \geq x_{lim} \tag{48}$$

We can calculate average and max time for travelling

$v_{max} = 1$ m/s

$a = 1$ m/s^2

$$x_{lim}=\frac{v_{max}^2}{a}=1\ m$$

x ..... according to table.1

Table.2 Times for transporting tools

		Manipulator within storage	Exchange station	Loading unloading
t_r [sec]	average	2,02	2,26	2,77
	max	3,72	3,10	4,06

From table.2 is evident that value of time for travelling will not be main part of time of the exchange.

4.5. Working cycle of manipulator

Working cycle of manipulator is in (Fig. 14) and has these parts:

- travelling to starting address(t_4)
- gripping the unit with tool (t_2 = 7 sec)
- travelling of the target address (t_4)
- putting the unit with tool (t_3 = 4 sec)

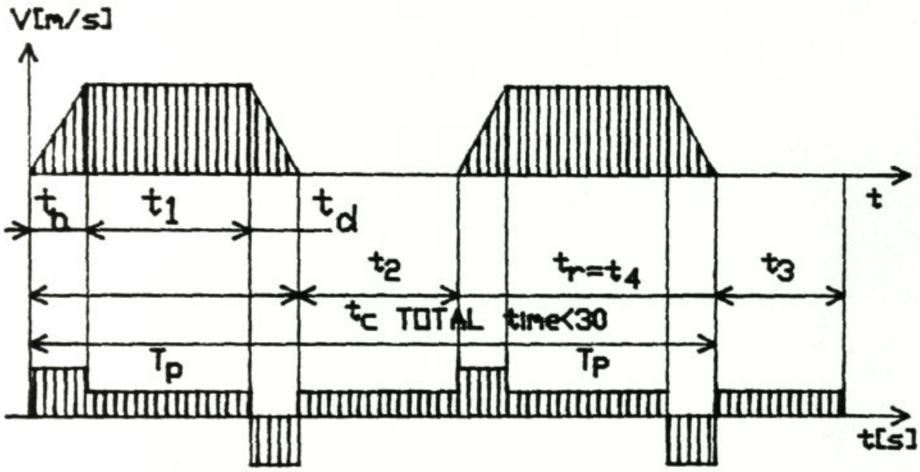

Fig. 14. Working cycle of the manipulator

For exchanging the tool two cycles mentioned above are necessary. The first cycle is for putting the used tool in the magazine, the second one for transporting the new tool in the exchange unit. The time for complete exchange then will be

$$t_c=4\,.\,t_4+2\,.\,t_3+2\,.\,t_2 \qquad (49)$$

Table.3 Times for changing the tools

	Ramp acc/decc $a=1m/s^2$
$t_{caverage}$ [sec]	31,04
t_{cmax} [sec]	34,40

$$t_{c\ average}=4.t_4+2.t_3+2.t_2=$$
$$=4.2,26+2.4+2.7=31,04\ [sec]$$

$$t_{c\ max}=4.t_4+2.t_3+2.t_2=$$
$$=4.3,1+2.4+2.7=34,40\ [sec]$$

5. DESIGN OF SERVODRIVES

For the tool manipulator in axis x and y, the maximum average time for the transport from storage to the automatic tool changer and back in Tmax = 30 sec.

Kinematic diagram for servodrive with position feed back travelling in x-axis is in (Fig. 15) and for stroke in (Fig. 16).

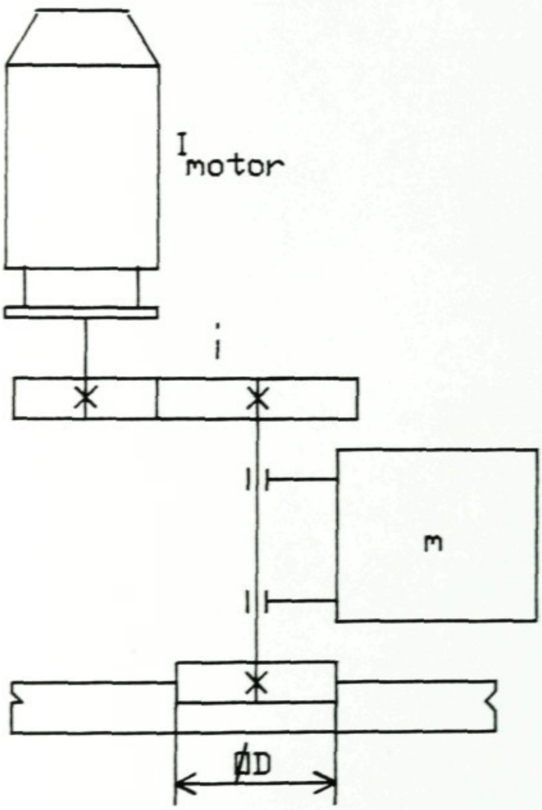

Fig. 15 Kinematic diagram of horizontal X-axis

And other parameters

velocity 1 m/s (60 m/min)

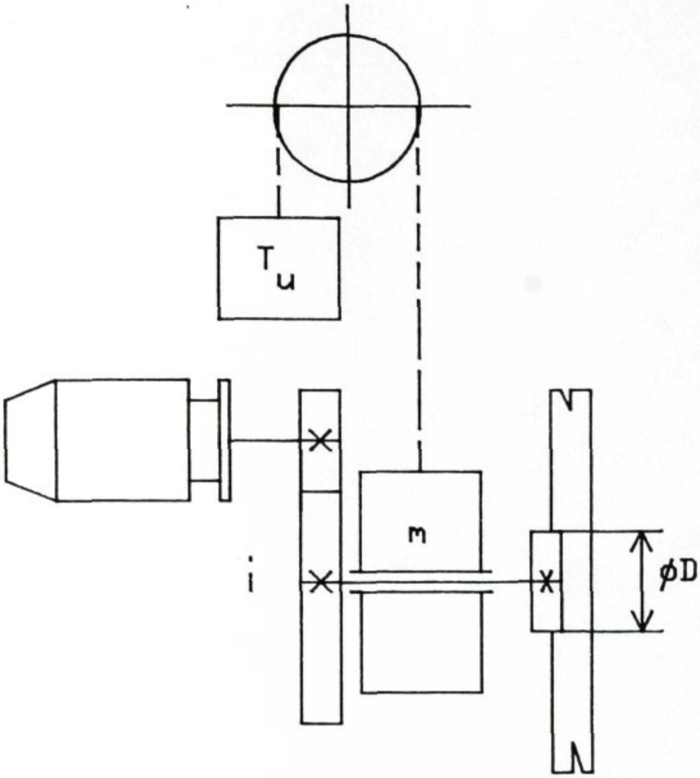

Fig. 16 Kinematic diagram of the vertical Y-axis

total accuracy of positioning 0,1 mm

mass of the x-axis 830 kg

mass of the y-axis (30 kg tool included) 250 kg

mass of the balance weight of the y-axis 220 kg

minimum position gain kv = 5 s^{-1}

total number of tools 144 /1/

5.1. Kinematic Design

We suppose using of Siemens AC drive, whose motors gives full power at 6000 rev/min (see working area of motor Fig. 17) Suitable gearing ratio gives motor velocity in area of these speeds.

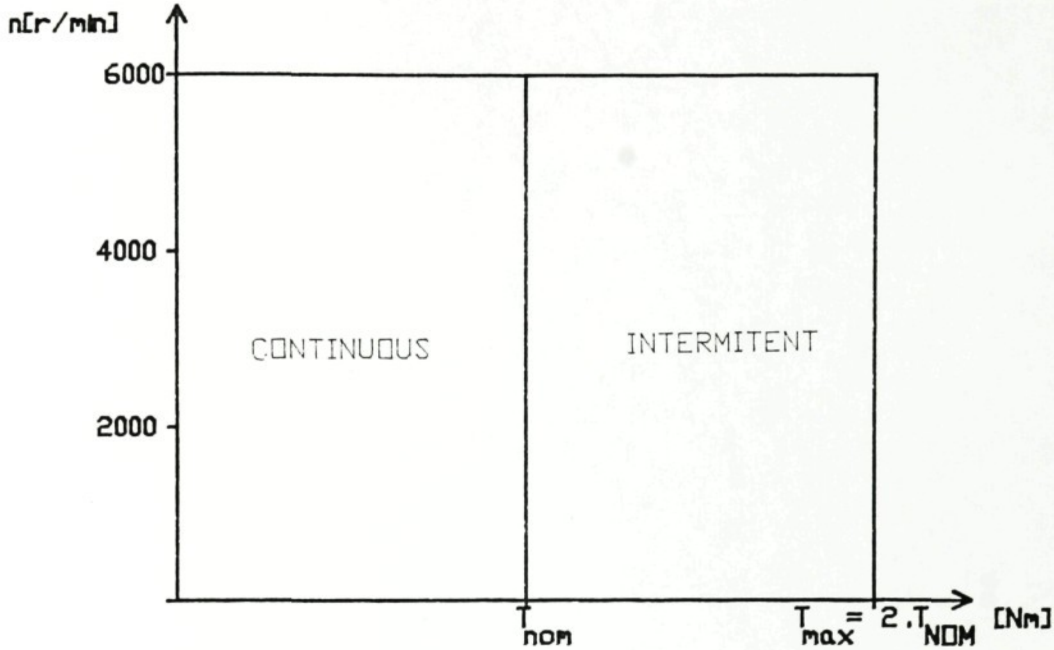

Fig. 17 Working area of AC Siemens drive

For safety we use 5000 rpm only Total gearing ratio is then:

$$i_c = \frac{v}{\omega_{mot}} = \frac{1}{5000.\frac{2\pi}{60}} = 1.91.10^{-3}\ [m/rad] \tag{50}$$

Moment of inertia for gearing ratio reduced on motor shaft estimated on:

$$I_{gear} = 3.10^{-3}\ [kg.m^2] \tag{51}$$

Gearing ratio will be identical by side travel and stroke of the manipulator.

5.2. Static and dynamic design

Total passive force estimated for both drives of size travelling force

$$F_P = 500 \text{ N}$$

Its converted on motor shaft is given

T_P = Passive torque

$$T_P = F_P . i_C = 500.1,91.10^{-3} = 0,955 \; [N.m] \qquad (52)$$

Angular acceleration on motor shaft start ramping and range at a = 1 [m/s^2]

$$\varepsilon = \frac{a}{i_c} = \frac{1}{1,9.10^{-3}} = 525 \; [rad/s^2]$$

manipulator Travel in x-axis

Reflected moment of travel inertia

$$I_{refl} = m . i_C^2 = 830.(1,9.10^{-3})^2 = 0.003 \; [kg.m^2] \qquad (53)$$

and the torque for acceleration without motor

$$T_{max1} = T_P + (I_{refL} + I_{gear}) . \varepsilon = \\ = 0,955 + (3.10^{-3} + 3.10^{-3}).525 = 4,1 \; [N.m] \qquad (54)$$

$T_{nom} \approx T_{max1}$ - motor torque

Then the type of motor will be 1FT5 064 4.5 [N.m] (6000 rpm)

I_{total} = Total moment of inertia

$$I_{Total} = I_{refl} + I_{Gear} + I_m = \\ = 0,003 + 0,003 + 8,3.10^{-4} = 0,007\ [kg.m^2] \tag{55}$$

And torque at acceleration and decceleration will be

$$T_{Tot} = T_P + I_{Tot}.\varepsilon = \\ = 0,955 + 0,007.525 = 4,675\ [N.m] \tag{56}$$

$$T_{Tot} \leq 1,6.T_{nom}$$

The biggest values of torque for ramp acceleration and deceleration is in table 4.

Table 4. maximum values of torque at acceleration and deceleration in the x-axis.

	Acceleration	Deceleration
Ramp acceleration	T_{Total} [N.m]	
a = 1 [m/s^2]	4,675	-2,72

Acceleration torque in permissible limits with great safety. But we use this motor because the next smaller one has only 2.2 N.m nominal torque which is too small for this purpose.

Manipulator stroke in y-axis

Reflected moment of inertia is

$$I_{refL} = (m+m_b) . i_c^2 = \\ = (250+220) . (1,91.10^{-3})^2 = 0,0017 \ [kg.m^2] \quad (57)$$

Here is unbalancing weight on the motor acting in the next side so the torque unbalancing will be calculated in this form:

$$T_u = (m-m_b) . i_c . g = \\ = (250-220) . 1,91.10^{-3} . 9,81 = 0,56 \ [N.m] \quad (58)$$

and the torque for acceleration is

$$T_{max1} = T_u + T_p + (I_{refL} + I_{gear}) . \varepsilon = \\ = 0,56+0,955+(0,0017+0,003) . 525 = 4 \ [N.m] \quad (59)$$

Then the type of motor is the same 1FT5 064 4,5 N.m (6000 rpm)

Total moment of inertia reduced on motor shaft is

$$I_{Total} = I_m + I_{Gear} + I_{refL} = \\ = 0,00083+0,003+0,0017 = 0,0053 \ [kg.m^2] \quad (60)$$

In vertical movement we have two torques for acceleration and two for deceleration. The biggest torque for acceleration will be for the movement upwards (+ direction)

$$T_{up\text{-}a} = I_{Tot}.\varepsilon + T_p + T_u = \\ = 0{,}0053.525 + 0{,}955 + 0{,}56 = 4{,}3\ [N.m] \qquad (61)$$

Torque for deceleration for the movment upwards:

$$T_{up\text{-}d} = T_u + T_p - I_{Tot}.\varepsilon = \\ = 0{,}56 + 0{,}955 - 0{,}0057.525 = -1{,}47\ [N.m] \qquad (62)$$

and then we have tow acceleration down and deceleration down

$$T_{down\text{-}a} = T_u - T_p - I_{Tot}.\varepsilon = \\ = 0{,}56 - 0{,}955 - 0{,}0053.525 = -3{,}27\ [N.m] \qquad (63)$$

$$T_{down\text{-}d} = T_u - T_p + I_{Tot}.\varepsilon = \\ = 0{,}56 - 0{,}955 + 0{,}0053.525 = 2{,}47\ [N.m] \qquad (64)$$

<u>**Note**</u>: smaller motor 1FT5 062 has $T_{nom} = 2{,}2$ N.m and $T_{max} = 4{,}4$ N.m And the T_{TOT} which is calculated too near to the $T_{max} = 4{,}4$ N.m (see 61) so for this reason it is necessary to use the bigger motor 1FT5 064.

5.3. Calculation of the thermal load

At bigger acceleration than 1 $m.s^{-2}$ will be crossed nominal torque of the motor. Joule heat rising temperature in armature of the motor. The heat is proportional to the to the current and to the torque. The sum of the heat generated through the working cycle must be lower than heat generated by the nominal torque. Then we calculate the $T_{equivalent}$ for the cycle summing the time.

For horizontal movement it is clear, the $T_{eq} < T_{nom}$ but for more accuracy we do next calculation (see Fig. 14 and Tab. 4).

$$T_{equivalent} = \sqrt{\frac{2.T_a^2.t_a+T_p^2(t_2+t_3+2.t_1)+2.T_d^2 t_d}{t_c}} =$$

$$= \sqrt{\frac{(4,675)^2.1.2+(0,955)^2(7+4+2.0,26)+(-2,72)^2.1.2}{15,52}} =$$

$$= 2 \leq T_{nom}$$

Which is $T_{eq} \leq 4{,}5$ Nm ($T_{nominal}$)

$$t_d = t_a = \frac{v}{a} = \frac{1[m/s]}{1[m/s^2]} = 1\ s$$

$$t_4 = t_a+t_1+t_d = 2,26\ [s]$$

$$t_1 = 2,26-t_a-t_d = 0,26\ [s]$$

$$t_c = 15,52\ \text{sec}$$

<u>Note</u> $t_c = 31{,}04$ second but in the equivalent torque we have substituted a half of the complete cycle because the first half has the same source like

the second one. The torques for the 4 types acc/decc for the vertical movement are in table 5.

Table 5. Shows the biggest and smallest torques at acc/dec stroke.

	Acceleration	Deceleration
Ramp acceleration $a = 1$ [m/s^2]	T_{Total} [N.m]	
	4,3	-1,47
	-3,26	2,47

Know we shall calculate gearing ratio between motor and driven pinion. We use the old pinion with the pitch diameter 42.4 mm. Then the gearing ratio will be

$$i = 2.\frac{i_c}{D} = 2.\frac{1,91.10^{-3}}{42.4.10^{-3}} = 0,09$$

Which is i = 1:11.1

For this value of gearing ratio it is possible to use cycloidal gearbox which is manufactured especially for this type of motor. Specification of this gearbox is Series number of drawing 109776

ratio 1:11 (Δ ˉ 1%)

And the gear box is mounted directly on the motor shaft. So for both drives in X-axis and Y-axis we have two cycloidal gear boxes-two motors and two amplifiers.

The specification of motors is 1FT5 064

$T_{nom} = 4.5$ N.m $\qquad I_m = 0{,}00083$ kg.m^2

$I_{nom} = 8.7$ A $\quad \rightarrow \quad$ amplifier 12 A output

The motors are supplied with amplifiers and specification of amplifiers is 6SC611-2AA00

$I_{nom} = 12$ A $\qquad I_{max} = 24$ A

We have two variants of supplying the drives. The first one is using the power supply from the spindle and servo drives of the machine tool.

The second one is using separate power supply 6SC6 11 0-7 (11,5 A, 7 KW).

6. EXAMPLES OF MANIPULATOR UTILIZATION

For machining centres, there are a number of special - purpose tool storage systems, Pegard and OKK have developed system in which a rack adjacent to the machines carries over 180 tools. In the OKK system, a two-axis pick-and-place device transfers the tools between the rack and drum in 12 s. Pegard uses a manipulator at the spindle to exchange tools. Mori Seiki has a similar system, the tool begin transferred to the APC by the same trolleys used for work pieces. The disadvantage of these two system is that the spindle must be stopped while tools are changed. A weakness on many machining centres is that the tools can only be loaded into the APC at one station - the one adjacent to the arm that loads the tool into the spindle. Normally the tools can be loaded when the spindle is stationary. Since this precludes the use of fully automatic tool changing while the metal is being cut, such machines should not be selected for an FMS.

The German companies Fritz Werner and Herman Kolb, have produced systems with tool changers. In the Werner DFZ 360 cell, two four-axis horizontal machining centres are backed up by racks carrying some 120 tools. The tool changer runs across a gantry loader and is used to transfer both tools and work pieces. The loader picks up pallet by locating on a standard ISO taper. This is an excellent approach in theory and certainly it is the best to adopt an integrated tool transport system, but whether or not this one is particle depends on the cycles involved. For example the pallet/workpiece assemblies are much heavier than the tools, so that the loader may move rather slowly (Fig.18).

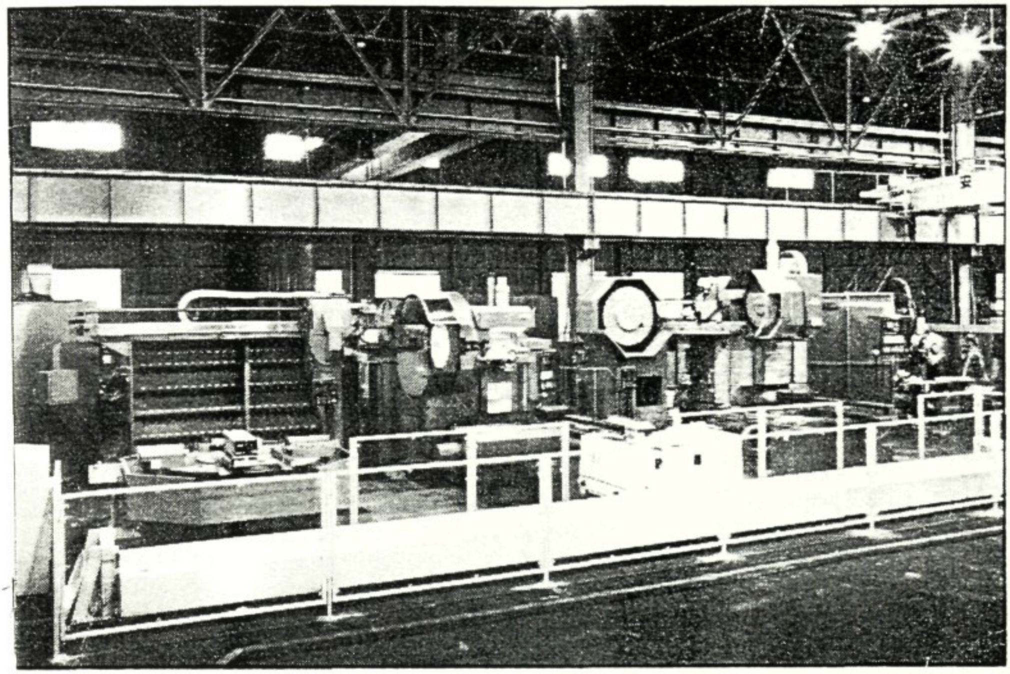

Fig. 18. Ancillary tools racks are now available with some machining centres

7. CONCLUSION

From technological point of view demand to change the tools in 30 second is the main criterion and must be submit to all proposals of tool manipulator. Temporal analysis is worked out in chapter four. This chapter explaines, that the time for exchange is possible to fulfil at using position servodrive with minimum time reserve. Because setting up the coordinates with position servodrive is fastest of the known ways it is impossible to use other than position servodrive.

Chapter five solves kinematic, static and dynamic ratios of the drive for the both horizontal and vertical movements.

Futher it is worked out thermal load of motor. Loading the motor at both drives in X-axis and Y-axis is within the allowable values.

Design of the drives for tool manipulator satisfy Basic requirement on manipulation with tools - so transporting used tool to storage and new tool in the exchange station in time which is very nearly to 30 second.

Replacing the old DC drive by the new AC one brings great savings in volume and mass so the next comparation is between these two drives.

The old DC drive Mezomatic 3 SHAT 90 M (see Fig.19)

$T_{nom} = 10$ N.m at 0 - 500 rpm

$T_{nom} = 6$ N.m at 1300 rpm (working speed)

$I_m = 0{,}01$ kg.m^2

mass = 36 kg

dimension of motor D = 168 mm, l = 526 mm

The new and improved AC drive SIEMENS series 611, motor 1FT5 064 (see fig.17)

T_{nom} = 4.5 N.m   at 0 - 6000 rpm

5000 rpm (working speed)

I_m = 0,00083 kg.m^2

mass = 8.5 kg

dimension of motor cross section 155 mm, l = 281 mm

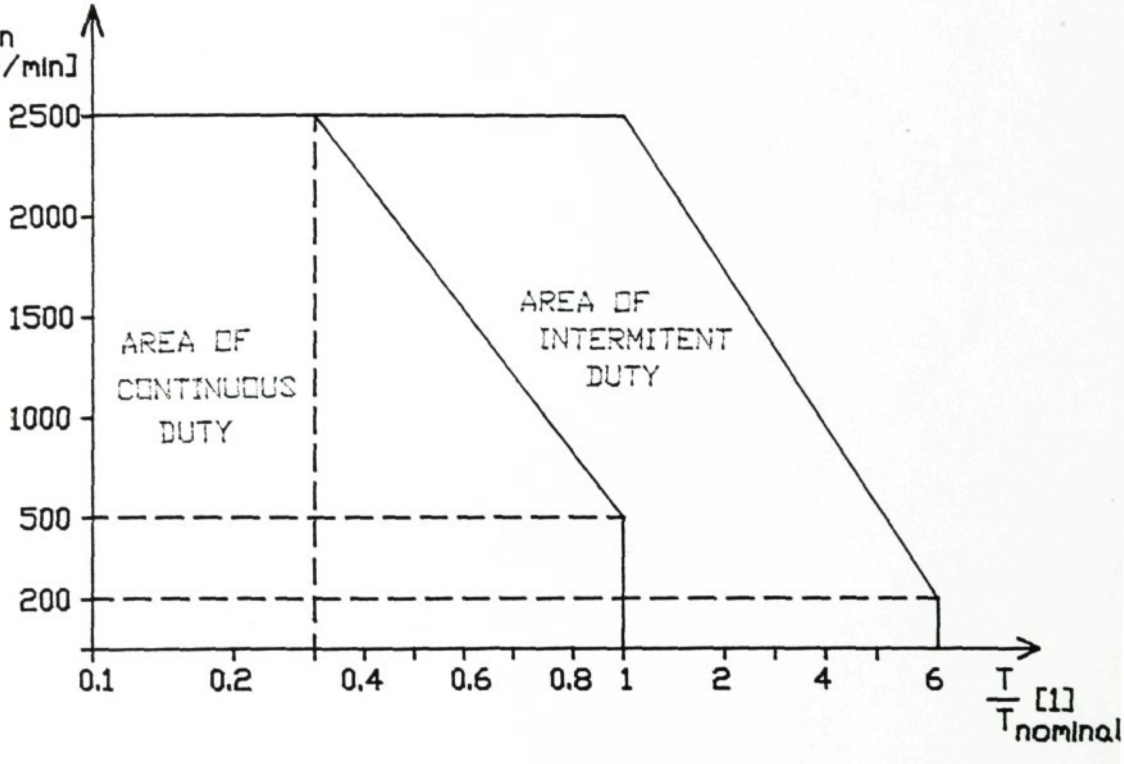

Fig. 19. Working area of DC drive Mezomatic 3 SHAT 90 M

ACKNOWLEDGEMENT

At the end of my diploma project I wish to thank my Supervisor Ing. Jan Skalla, CSc. from Department of manufacturing systems for his valuable contribution in solving this project and every teacher in this University who advised me and helped me accomplish my study in the faculty of Mechanical Engineering of the Technical University of Liberec.

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