DESIGN OF PARALLEL MICROMECHANISMS FOR KNOTTING OPERATION

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İZMİR

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ABSTRACT

DESIGN OF PARALLEL MICROMECHANISMS FOR KNOTTING OPERATIONS

This thesis covers a study on the design of micromechanisms which are capable of imitating the knotting operation and their applications on carpet manufacturing.

For this purpose, motion generation synthesis of a planar two degree-of-freedom serial manipulator is performed for a given path by using interpolation approximation. For a given four points, four design parameters are solved as a result of non-linear equations.

Also, analysis of each stages of knotting operation is kinematically performed for the design of a cam-actuated mechanism which is designed as an alternative concept. Results of these analysis are used for the design of cam profiles those of which actuates the manipulators

After design stage of knotting micromechanisms, fully automated carpet loom design is introduced for a real-life experiment of designed mechanisms. Finally, assembly considerations of carpet loom and knotting mechanisms are given for carpet manufacturing purpose.

ÖZET

DÜĞÜM OPERASYONUNDA KULLANILACAK PARALEL MİKROMEKANİZMALARIN TASARIMI

Bu tez düğüm atma işlemini taklit edebilen mikromekanizmaların tasarımsal çalışmasını ve bu mekanizmaların halı üretimine uygulamalarını kapsamaktadır.

Bu amaçla, öncelikle, düzlemsel iki serbestlik dereceli seri manipülatör sentezi verilen bir yörünge için interpolasyon yöntemiyle tamamlanmıştır. Verilen dört nokta için, manipülatörün dört dizayn parametresi lineer olmayan denklemlerin çözümlenmesi sonucunda bulunmuştur.

Kam sistemi ile hareket ettirilen ve alternatif konsept olarak tasarlanan düğüm mekanizmasının tasarımı için halı dokuma işleminin tüm evreleri kinematik olarak incelenmiştir. Bu analizlerin sonucu, manipülatörleri tahrik eden kam profillerinin tasarımında kullanılmıştır.

Tasarlanan düğüm mekanizmalarının halı üretiminde gerçek koşullarda denenebilmesi için otomatik halı tezgahının tasarımı anlatılmıştır. Son olarak, tasarlanan tezgahın ve mikromekanizmaların halı üretimi açısından montajında dikkat edilen noktalar verilmiştir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

HANDWOVEN CARPET TECHNOLOGY

1.1. Introduction

A mechanism can be defined as a system of bodies designed to convert motions and forces of one or several bodies into constrained motions and forces of other bodies. This conversion could be as a manner of planar or spatial by planar or spatial mechanisms, respectively.

In industrial applications, mechanisms are designed depending on their usage areas. The most important stage in these design processes is to define the dimensions of the linkage system, which satisfy the prescribed function, path or motion; those of which are the requirements of the desired task. Generally, for industrial applications, three types of manipulators are used: serial, parallel and hybrid.

Throughout the literature, many studies are proposed on the kinematic synthesis of the serial manipulators. Sandor and Erdman (1984) used the complex vector formulation for the dimensional design of a planar Revolute-Revolute (RR) chain. Later, McCarthy (1995) extended this formulation by applying the design of Cylindrical-Cylindrical (CC) chains.

Perez and McCarthy (2000) proposed a study on the synthesis of spatial RR manipulator to reach the given trajectory points. These tarjectory points were interpolated by double quaternions in order to obtain the complete trajectory. Krovi et al. (1998) examines the synthesis problem of coupled serial chains by using the loop closure equation and the necessary geometric constraints, where the joints of the manipulator are coupled via cables and pulleys. Mavroidis et al. (2001) solved the synthesis problem of a spatial serial RR manipulator for three given distinct spatial position by using homogeneous transformation matrix. For solving the synthesis equations arose in the problem, authors applied the Polynomial Elimination techniques. Ceccarelli (2002) introduced the term feasible workspace for a spatial RR manipulator, which is used as a region for computing required precision points for the synthesis procedure that constraints the design procedure. Innocenti (2005) studied on the positioning of the base of a two degree of freedom serial manipulator for maximazing the reachable desired points in the space as much as possible.

Su and McCarthy (2005) examine the synthesis problem of a spatial serial RPS manipulator for arbitrarily choosen set of spatial positions, where the polynomial continuation method was applied to synthesis polynomial which lead to a wide variation of possible solutions.

Lee and Mavroidis (2003), also used the polynomial continuation method for the solution of motion generation synthesis of spatial 3R serial manipulator, where Denavit-Hartenberg notation and 4x4 transformation matrix method were applied to problem. Ceccarelli (1995) proposed a synthesis method for 3R serial manipulator based on the workspace boundary of the mentioned manipulator. Jimenez et al. (1997) developed a general methodology for the synthesis problem of spatial mechanisms by using only the natural cartesian coordinates of the system.

Depart from serial manipulators, the synthesis problem of parallel mechanisms has been studied detaily over a period of time. Especially, there is a big amount of studies on the dimensional design of four-bar linkage system. Todorov (2002) extends the number of possible solutions for a function generation four-bar synthesis problem by applying Chebsyev's best polynomial approximation to Freudenstein's equation (1955). Alizade and Kilit (2005) applied an approximation method, which transforms the non-linear equation sets into a set of linear equations, to find the five design parameters of a spherical four-bar linkage by five given precision points. Hongying et al. (2006) developed a software, which uses coupler-angle function for the synthesis of a four-bar mechanism. This software was applied to the design of crank-rocker mechanism for the given 20 coupler points.

Simionescu and Beale (2002) proposed a new objective function for the optimum function generation synthesis of a four-bar mechanism. By using this square-max norm based objective function, smaller and more uniform deviations between the desired function and the function generated by the mechanism could be reached. Authors also examined the effects of the design parameters on the performance of an Ackermann steering system.

Dimensional synthesis of planar four-bar mechanisms had been studied extensively as mentioned above. Many analytical and graphical techniques had been developed where the problem of solving higher degree polynomials arised. For this purpose, numerical methods were applied to the synthesis problem. Despite their capabilities of solving higher degree polynomials, numerical methods require "a good initial guesses" on the design parameters. Shiakolas et al.(2002) proposed "Geometric

Centroid of Precision Points", a method, which provides initial bonds for the design variables. This method is applied to the synhtesis problem of four-bar system with differential evolution optimization, where the complexity of the problem increased by the additional constraints that include the number of precision points, the correct order of precision points to be visited and the coupler curve to be traced.

Generally, analytical or graphical synthesis of mechanisms need the precision points on the desired trajectory. These points defines the distinct positions of the end-effector. For the case of mechanism synthesis, which generates a particular curve, it becomes impossible to solve analytically due to higher degree polynomials. For this problem, Hoskins and Kramer (1993) proposed a method, Radial Basis Function , based on artificial neural networks (ANN) to select appropriate link dimensions which generates a user-defined curve. Vasiliu and Yannou (2000) developed an ANN method for mapping the coupler curves of prescribed mechanisms, which leads to generate new linkage systems for newly prescribed coupler curves.

Also, in the subject of handmade carpet manufacturing Topalbekiroğlu (2005) and et al. have applied the kinematic synthesis and analysis procedure to the mechanisms that are proposed for the weaving sections of handmade carpets by Turkish knots.

1.2. History of Carpet Weaving Process

Although, it is uncertain, where the first rug or carpet had been woven, many historians assume their origin as Central Asia. Many tribes and clans had lived in this part of Asia until a popular explosion caused people migrate to the western parts of Asia. These immigrants had to stand the extreme weather conditions during their migrations where the need of waterproof and isolating shelter arouse. This shelter had to be easy to establish and portable. In order to keep themselves from rain, snow and humidity from soil, nomads learn to use rugs that are widely made from goat hair. Covering their tents' roofs by these flatweaven rugs, they not only made their tents waterproof but also keep them cool during hot summer season.

Apart from being used as a shelter, rugs had become a design object by adding pagan symbol while weaving and used as separators for dividing tents into rooms. Women used rugs to make cradles for their sleeping babies whereas men use them as travelers' bag while riding.

Over a period of time, by using animal pelts as a model, piles were added to rugs which were considered as beds instead of dried leaves.

As mentioned before, time and location of the first woven carpet is still unknown. However, the oldest surviving woven carpet was found on an ancient tomb which was belonging to a Sycthian prince in Pazyryk Valley in Altai Mountains (Figure 1.1). Carpet is 3,62 square meter and contains 347000 knots per square meter which makes it invaluable. Motifs on the carpet belonged to Persian Achaeminian, a Persian dynasty who ruled from 550 to 331 BC, so the carpet is believed woven in 5th century BC.

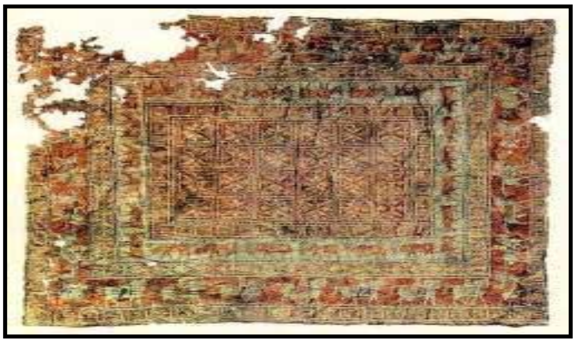


Figure 1.1 The carpet found on Scythian prince's Tomb (B.C 500)
(Source: Persian Carpet Guide)

Today, it is rare to find carpets that last over 500 years. Many of them are displayed in the museums around the world.

In Turkey, the oldest known carpets are dated to have been from 12th and 13th centuries and made by Seljuks. Eight of them were founded in Alaatin Mosque located in Konya by German Consul Loytred in 1905 (Figure 1.2). These carpets are displayed in Mevlana Museum and Kier Collection in London.

Figure 1.2 Oldest carpet weaven in Anatolia
(Source: RugIdea)

1.3. Carpet Weaving Process

Mechanized or not, carpet weaving process has many sections including; production of the knot material, design of the motifs and patterns, construction of the loom depending on the size of the carpet and inspection. All of these stages need great patience, attention and highly trained workers. As the whole process carried out by hand, in handwoven carpets, an error during any of these stages results in time and labor consumption. In order to design a robot for this purpose, it would be useful to examine each of these sections as shown in Figure 1.3.

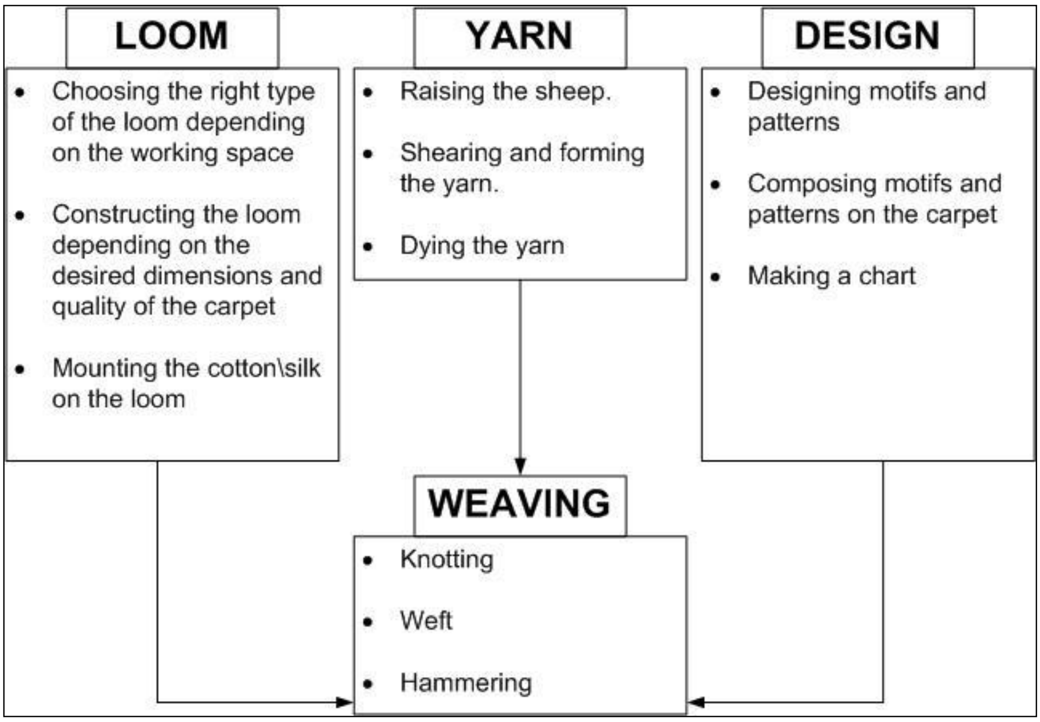


Figure 1.3 Process Scheme for Carpet Weaving

1.3.1 Loom

Loom is a vital part of the carpet weaving process. It both provides required tension to the warps to be interweaved with weft threads and adjusts the space between them which has great influence on the quality of the carpet. Looms has selection criterias depending on the dimension and quality of the carpet and also workspace of the worker.

Handmade carpets are manufactured in different sizes based on their usage areas as rugs, wall hangings and covers for table or sofas. Depending on their dimensions, carpets are widely classified into eight types (Table 1.1). Although the names are the same for all regions, the carpets may show minor differences of dimension. While some regions manufacture carpets in any desired sizes, others manufacture carpets in standard sizes. Note that, the size of the carpet, especially the width, depends on the size of the loom. Thus, at the design stage of the carpet manufacturing, a suitable loom size for the design should be selected.

Table 1.1 Standard Dimensions for Handwoven Carpets

Name	Dimensions (cm.)
Küçük Yastık (Pillow)	40 x 25
Yastık	100 x 60
Çeyrek	135 x 90
Seccade (Prayer Rug)	180 x 120 – 200x 130
Karyola	220 x 150
Kelle	300 x 200
Taban	Over 6 sq. meters
Yolluk	Desired sizes

During their migrations, nomads of Central Asia did not have enough space or time for constructing big looms for their weaving processes. As a result, they invented horizontal loom (Figure 1.4) that is simple and easy to assemble or disassemble. This type of loom could be staked to the ground or supported by sidepieces on the ground. The tension needed for warp threads can be obtained by the use of wedges. As mentioned above, this type of loom is suitable mostly for nomadic people. However, it is widely used in the eastern part of Turkey. Carpets (or rugs) produced on these looms are generally small and has lower quality compared to vertical looms.

Figure 1.4 Horizontal Loom
(Source: Picassa)

When compared with the horizontal looms, the vertical looms (Figure 1.5) are permanent and used in towns and villages. The weaver using this type of loom sits and weaves from the bottom to the top that makes this type more comfortable to operate. This type of looms consists of two vertical posts, which are connected by two strong beams. This type of looms, there is no restriction for the length of the carpet as the woven part could be wrapped on the bottom beam. The tension required for weaving is obtained by adjusting the distance between the beams. The weaver should wrap the woven part on the lower beam, so by only changing the unwoven part and slip away the woven part, weaver could weave the whole carpet in any length without standing. This type of looms are widely used in western part of Turkey, Iran and India.

Figure 1.5 Vertical Loom
(Source: Alfiber Arts)

1.3.2 Yarn

If the loom is an exo-skeleton of a carpet, yarn should be considered as a skin. Despite being different types of yarns, warps, wefts and knots are commonly made of same material which is mostly wool. In Turkey, there are five basic materials for handwoven carpet that have various thicknesses and mechanical properties which results in different types and qualities of carpets.

- **Sheep Wool:** Wool is the most common material used in carpets. Due to having excellent grazing lands for sheep, wool is the only material for carpets in western parts of Anatolia. The quality of the wool changes with the climate, breed of the sheep and season of the shearing. Sheep that breed in warm regions have dry and brittle wool. During weaving process this type of wools generally breaks so easily which is a problem for tight knotting in order to have a good quality. In cold regions at higher elevations with good grazing lands, the sheep grow a full fleece to keep warm and their bodies store fat which then translates to a high lanolin content used in fiber length of 8-10 cm.

- **Cotton:** Cotton is usually used as a base material for the carpet (warp and weft). Compared to wool, cotton has stronger fiber and less elasticity which gives chance to tie tighter knots on the warps. Consequently, cotton based carpets have more knot density than the woolen ones that results in better quality.

- **Goat Hair:** Goat hair is widely used as side bindings of the carpets. However they are used for weaving saddle bags, cushions and stacks more frequently.

- **Floss Silk:** In carpets woven only in Kayseri, floss silk, which is a kind of mercerized cotton, is used. Floss silk is used as pile knots on the cotton based carpets. It is obtained by mixing cypress tree fibers with cotton that has been washed in citric acid. It is as strong as other carpet materials and is also easily dyed, making possible to produce wide range of colors.

- **Pure Silk:** The silk used in Turkish carpet comes from silk cocoons in Bursa. It has a very high tensile strength which makes silk invaluable material for making high quality carpets. As the silk is thinner and stronger than other materials, knot density of a silk woven carpet is the highest among all of the types. A normal quality silk carpet should have 1,000,000 knots per square meter which can rise up to 3,240,000.

Another important aspect in yarn preparation is the dying. In order to weave the motifs on the carpet, different colors of piles needed. For this purpose, after being prepared for weaving, by using chemical or natural substances, yarns are boiled up to different colors. Despite having more color variety by using synthetic dyes, natural dyes widely selected in Anatolia. Carpets, which are woven with natural dyed-yarns, have better resistance to lighten more than the chromatic dyes. Moreover, naturally dyed carpets are exposed to sun so that the colors fade gradually to the year ultimate harmony and beauty.

Natural dyes are obtained by boiling the plants until the desired colors are extracted. In order to make the color absorbed by the yarn a second plant is added to dye that is called as mordant. Some plants used for natural dying are given below.

- **Dyes Woad (Blue):** From this plant dark or light blue tones are produced by the length of boiling time. It is found along the edges of fields growing wild in Central and Western Anatolia.

- **Madder (Red):** The roots of this plant are known as madder. “Rose madder” was a standard color on the palettes of the painters of Renaissance and today.

- **Ox-Eye Chamomile (Bright Yellow):** During the spring, this plant can be found all over Anatolia. These flowers, fresh or dried, used along with an alum mordant, produce a bright yellow.

- **Walnut Tree (Brown):** These trees can be found in the forests of eastern Anatolia. The effective coloring agent is the brown dye, juglone, which adheres directly to wool fibers without a mordant.

- **Pomegranate Tree (Bronish yellow and Brown to Black):** This tree grows in the mild regions of Western, Southwestern and Northeastern Anatolia. The fresh or dried skin of the fruit is used for dying. If an alum mordant is used a yellow brownish color will be formed. If an iron mordant is used, a brownish black shade will be formed. In Oriental carpets and kilims, the pomegranate is a symbol of fertility and abundance related to its many seeds.

- **Buckthorne (Deep Yellow):** This plant grows only in Turkey on slopes with altitude up to 3000 meters. The unripe fruits, fresh or dried, are used for creating the dyes. When an alum mordant is used, a deep yellow color will be formed. This color dye is often used to obtain secondary and tertiary colors.

- **Supurge (Yellow):** This plant grows throughout Anatolia. All parts of the plant, except the roots are used for creating yellow dye.

- **Bast Hemp (Brilliant Yellow):** This dye is not used as often as other yellow dyes. This plant grows on the mountains of Central and Eastern Anatolia. The strong color extracted from this plant is often mistaken for a chemical dye and for this reason it’s not popular in Western Anatolia Workshops where the export carpets are woven.

- **Tree-Leaved Sage (Yellow):** This herb can be found in most Mediterranean regions. It blooms on the dry hill sides from March up to August. The leaves and stems, fresh or dried, are suitable for dying.

In the design stage, designer should not only consider the motifs and patterns but also the meanings expressed by the colors. For instance, red expresses wealth, joy and happiness where green symbolize the heaven. Blue expresses nobility and grandeur; yellow is believed to keep evil away where black symbolizes the purification from worries.

1.3.3 Design

Designs used in carpets usually consist of inner field and a border (Figure 1.6). Borders are designed to emphasize the limits and isolate the inner field whereas to control the implied movements of the interior pattern. The inner field and the border must be harmonized pleasingly by remaining distinctly.

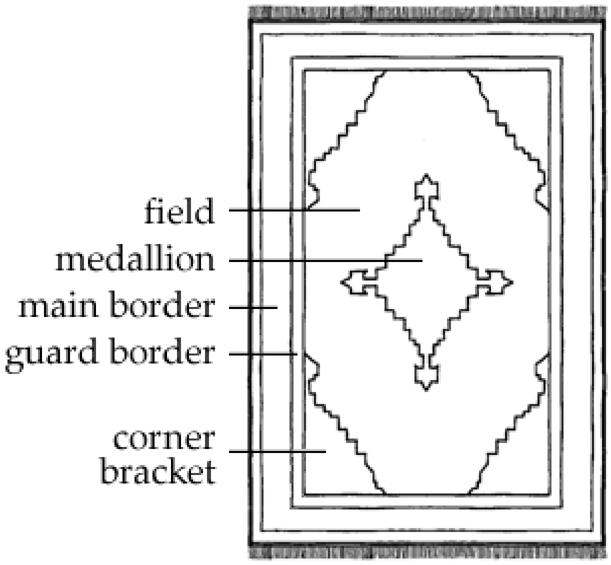
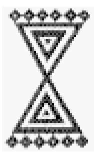
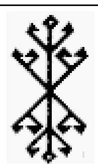
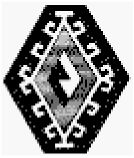
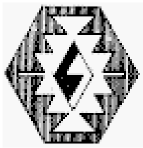
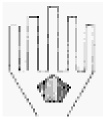
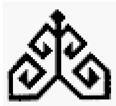
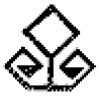
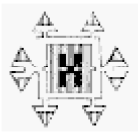
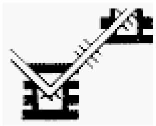
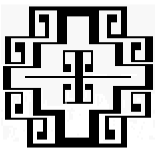
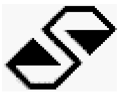
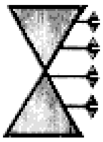


Figure 1.6 General design layout of a Turkish Carpet
(Source: Bazaar Turkey)

The borders are constructed with three main elements; main band, inner guard border and outer guard border. The width of main bands changes with the size of the carpet and the patterns are used in inner field in order to keep the harmony. Guard borders are the subordinate bands on either side of the main band. The design of the inner field consists of centered medallion, emphasizes the “massage” of the carpet, surrounded by repeating pattern. Some types of medallion and patterns along with their meanings are given in Table 1.2.

Table 1.2 Medallion types and their meanings

Design	Meaning
 	Hair Band expresses the will of a young woman to get married. By tradition in Anatolia, the girls keep their hair long and will not cut it until they get married.

 	Inherited by Far East, Ying and Yang denotes love and unity between man and woman. A dot of the opposite color in each half implies that nothing is pure in nature.
 	This motif implies that the weaver gives birth to a boy. Hands on Hips represents that she is very proud.
 	Ram's Horn represents the fertility and heroism.
 	The Chest Comb is the symbol of marriage and happiness. The chest implies the girl's longing for marriage, since they contain her dowry.
 	These symbols used for to represent the relationship between sexes and proliferation.
 	Family or clan symbols are used widely in tribal people to mark their possessions.
 	Bird symbols have different meanings. Birds of pray, like falcon and hawk implies the power which is widely used by Seljuk and Ottomans. The phoenix and dragon fighting represents the coming of spring rain.

Once, the general composition of the carpet is prepared which includes the selection of medallion, inner field and the borders, the motifs are drawn out on paper. Appropriate with the composition, the colors of the elements are decided. The layout of the carpet than transferred to a chart (Figure 1.7), which is divided by many squares. Each of these squares defines the coordinate of a single knot on the whole carpet.

Figure 1.7 Chart of a Carpet Design

1.3.4 Weaving Process

Weaving process is the simplest, on the other hand, the most tiring stage in carpet manufacturing. In this stage, warps are attached to the loom and stretched. For tight knotting, which yields to good quality, warps' tension and the space between the warps are vital. As the yarns get thinner under the tensile stress, when appropriate force is applied to the warps, more warps, which means more knots, could be placed in the unit area. Increase in the number of thread in the unit area leads to better quality carpets. The space between warps is another important aspect for the quality. If the space is too small, warps would get crossed which leads to a fatal error in the weaving process. On the other hand, if the space is too large, as fewer knots could be tighten and the quality of carpet gets lower.

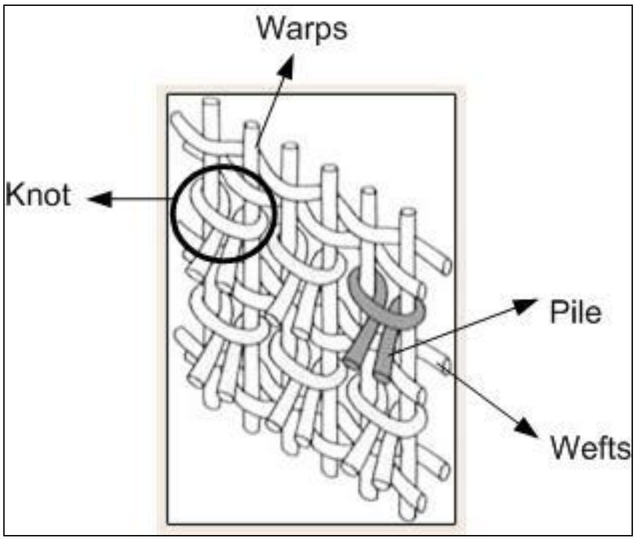


Figure 1.8 Yarn types used in carpets

(Source: Fibre to Fashion)

After attaching the warp yarns on the loom, weft yarns are crossed through them which is called wefting. In this process, warps are separated as seen in Figure 1.9 and heddle carries the weft yarn that passes through them. For the reverse, warps are crossed while the heddle is passing.

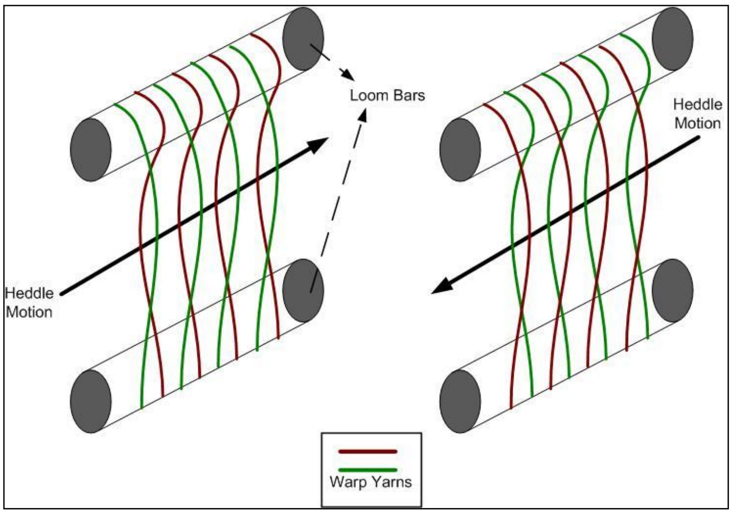


Figure 1.9 Wefting Process

Weft threads are used for constructing the base for the knots (Figure 1.10). Knots are strongly pulled down on these crossed threads on the warps after being woven. By other words, weft threads locate the knots on the carpet during weaving process. After each row of knots is completed new weft threads are woven by using the heddle.

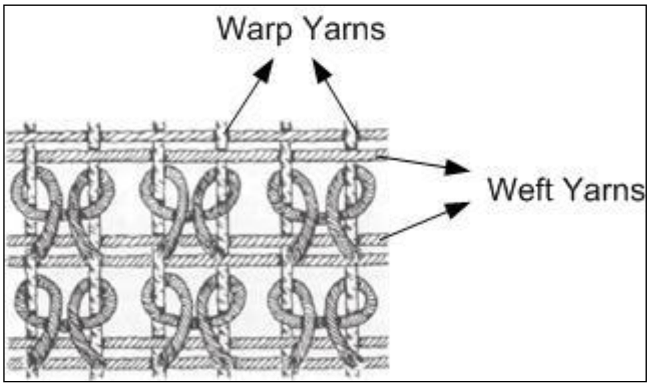


Figure 1.10 Weft Threads in Carpets
(Source: Gallery Çetiz)

Weft threads are also used in kilim manufacturing. By only using weft and warp threads, mono-colored rugs and kilims (Figure 1.11) are manufactured. These types of rugs are especially used in mosques.

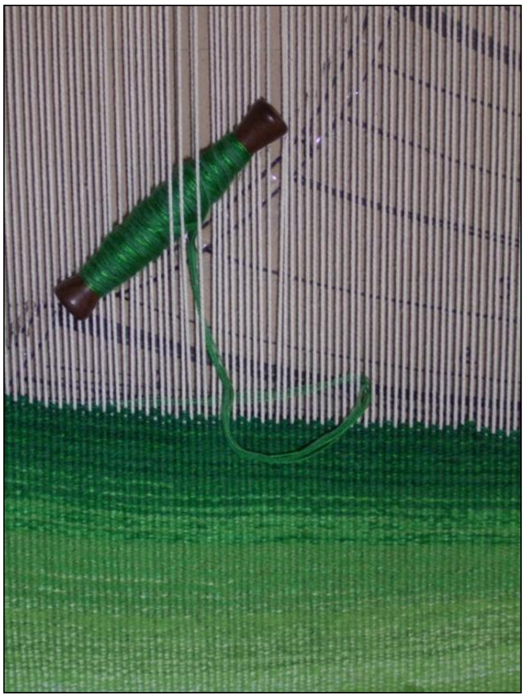


Figure 1.11 Weft threads in Kilim manufacturing
(Source: Muraliter)

Following the wefting process, knots are being tightened. In this process, weaver takes some pile yarn in the desired color shown in the chart, and pulled two neighbor warp yarns. Depending on their type (symmetrical or unsymmetrical), knots are tightened to these neighbor yarns and pulled down to the weft threaded section. Weft threads are the boundaries of the knotted row.

Although, there are many knot types, two of them are widely used in handwoven carpets. The Persian knot (Figure 1.12), also called as unsymmetrical knot, widely used in Afghanistan, China, India, Iran, Nepal and Pakistan. In this type of knot, the pile yarn twists one string of a basis and the second – only half. The advantage of this technique is that it does not leave any gap between the piles of the knots which gives a smoother appearance.

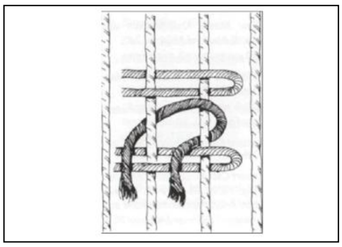


Figure 1.12 Illustration of a Persian Knot
(Source: Gallery Çetiz)

The other type of knot is known as Turkish knot (Figure 1.13) which is also known as symmetrical or Ghordes knot. This type of knot especially used in Armenia, Iran and Turkey. This type of knot symmetrically matches around two neighbor warps, which are completely twisted by pile yarn. In this type, there are some little gaps which makes it more fluffy.

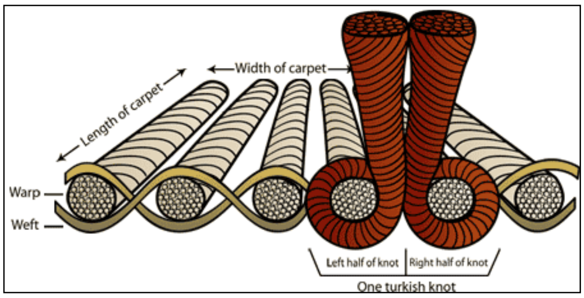


Figure 1.13 Illustration of a Turkish Knot
(Source: Handknotting Wordpress)

This process is followed by wefting again. However, before weaving a new row, all the threads, weft and knots, are tightened by hammering. For this process, the weaver used a tool called, tarak (Figure 1.14), which is made of leaves of metal separated by an appropriate gap with respect to the warp yarns. By hitting on the woven section, the gap between threaded rows is decreased which increases the knot density in the unite area and relatively the quality.

Figure 1.14 Hammering process
(Source: American Home Rugs)

CHAPTER 2

DESIGN OF WEAVER MECHANISM

2.1. Design of Weaving Mechanism by Using Manipulators

2.1.1 Kinematic Synthesis

The problem of kinematic analysis (direct and inverse task) and synthesis (dimensional synthesis) of mechanisms and manipulators can be solved by analytical methods those allow to present a position function in the form of obvious or non-obvious. Analytical expressions also allow to perform qualitative analysis (workspace, singularity) of interconnected parameters of mechanism's structure.

The presence of analytical solution in the form of obvious allows reducing computer time of numerical solution. This advantage is very important for manipulators as the mathematical models of kinematic analysis are used for control system. By describing the analytical dependence between mechanism's structure parameters and input(s) coordinates, position, velocity and acceleration functions will be described in the following form:

$$\overline{\phi_j} = f(\overline{c}, \overline{q_i});\ \dot{\overline{\phi_j}} = f(\overline{c}, \overline{q_i}, \dot{\overline{q_i}});\ \ddot{\overline{\phi_j}} = f(\overline{c}, \overline{q_i}, \dot{\overline{q_i}}, \ddot{\overline{q_i}}) \qquad (2.1)$$

If position, velocity and acceleration functions are given in the form of obvious, Eq. (2.1) yields;

$$F_j(\overline{c}, \overline{\phi}_j, \overline{q}_i) = 0;\ F_j(\overline{c}, \overline{\phi}_j, \overline{q}_i, \dot{\overline{q}}_i) = 0;\ F_j(\overline{c}, \overline{\phi}_j, \overline{q}_i, \dot{\overline{q}}_i, \ddot{\overline{q}}_i) = 0 \qquad (2.2)$$

where i=1,…,n and j=1,….,6.

In the decision of kinematic analysis of mechanisms and manipulators the problem of defining input coordinates is arose in the form of obvious or non-obvious. If the solution is in the form of non-obvious, the type of function Eq. (2.2) is preserved. Solving Eq. (2.2) in the form of obvious, an input coordinate and its first and second derivatives are determined as follows,

$$\overline{q}_i = f(\overline{c}, \overline{\phi}_j),\ \dot{\overline{q}}_i = f(\overline{c}, \overline{\phi}_j, \dot{\overline{\phi}}_j),\ \ddot{\overline{q}}_i = f(\overline{c}, \overline{\phi}_j, \dot{\overline{\phi}}_j, \ddot{\overline{\phi}}_j) \qquad (2.3)$$

where;

$\bar{c}$ is the vector of constant construction parameters of mechanism or manipulator,

$\bar{q}_i, \dot{\bar{q}}_i, \ddot{\bar{q}}_i$ are vectors of input coordinate and its first and second derivatives respectively,

$\bar{\phi}_j, \dot{\bar{\phi}}_j, \ddot{\bar{\phi}}_j$ are vectors of position functions, velocity and acceleration of output link of mechanism or manipulator.

Eqs. 2.1-2.3 shows that for generating technology process, usually motion of rigid body and its elements are given by independent displacement coordinates or by some combinations with its derivatives.

It is known that displacement (position and orientation) of a rigid body in space are defined by six independent parameters. If range of functional matrix of displacement equations of a rigid body (2.1) equal to 6, it means that the number of independent parameters describe the degree of freedom of rigid body in space (j_{max}=6).

Displacement of rigid body's elements (point with line, line, line in space, orientation of rigid body, position of rigid body in space or in plane, position of unit vector in space or in place trace of a point in plane and so on....) are defined by independent coordinates. The number of independent coordinate that equal to five or less position of rigid body's element respectively are determined by degree of freedom of work organ (j_{max}=5-1).

It is clear that degree of freedom of mechanism or manipulator can be less, equal or more than the degree of freedom of work organ ($i \leq j_{max}$ or $i \geq j_{max}$). If mobility of mechanism or manipulator is equal to the number of independent coordinates ($i=j_{max}$) it is received mechanism or manipulator with sufficiently mobility generated displacement of rigid body or its elements.

If number of independent coordinate of work organ j is generated by mechanism or manipulator on finite sets combination of input parameters i=1,....,n, so there are finite sets of combinations of mechanism generating displacement of rigid body or its elements ($i \geq j_{max}$). This kind of mechanical system called mechanism or manipulator with finite sets mobility.

In the case when the number of input parameters i=1,....,n one less than the number of independent parameters j, that mechanism or manipulator generating motion of rigid body or its element when $i < j_{max}$ are called mechanism or manipulator with insufficient mobility.

Kinematical vector $\bar{c}$ describes a kinematic chain, joined work organ to fixed frame. Kinematic chains lay over different constraint for work organ motion (or platform). These constraints are described by equations of kinematic chains in the form of Eq. (2.1-2.3). Parameter $\bar{c}$ is used in chains in the Eqs. (2.1-2.2) as parameter of kinematic analysis of mechanisms or manipulators with sufficiently or finite sets mobility respectively. But for mechanisms and manipulators with insufficient mobility the vector $\bar{c}$ in Eq. (2.3) describe a task of kinematic analysis and kinematic synthesis. Now lets make out the way of kinematic synthesis problem for defining parameters of vector $\bar{c}$.

It is required to design mechanism or manipulator in the best possible manner reproducing given function,

$$y = F(x)\ ,\ \ x \in D \tag{2.4}$$

where

x- vector of input parameters,

y- required output parameter, corresponding to input x.

Usually mechanisms or manipulators are defined by their mathematical model $F(\bar{c}, \bar{x})$ and generate the following function:

$$y_m = F(\bar{x}, \bar{c}), x \in D \tag{2.5}$$

where,

y_m – generated by mechanism or manipulator functions,

$F(\bar{x},\bar{c})$ - mathematical model of mechanism or manipulator which can be described by complex correlation or algorithm,

$\bar{c}$ - vector of mechanism's or manipulator's parameters.

Finding vector $\bar{c}$ is the main problem of kinematic synthesis that reduce to a minimum some criterion, describing an error between generating and given functions. In the capacity of criterion could be taken as the following functions:

$$J_1(\bar{c}) = \int_D q(x)[F(x,\bar{c}) - F(x)]^2 dx$$
$$J_2(\bar{c}) = \max_{x \in D}\{q(x)\left|F(x,\bar{c}) - F(x)\right|\} \quad (2.6)$$

or their discrete analogy,

$$J_1(\bar{c}) = \int_D q(x)[F(x,\bar{c}) - F(x)]^2 dx$$
$$J_2(\bar{c}) = \max_{x \in D}\{q(x)\left|F(x,\bar{c}) - F(x)\right|\} \quad (2.7)$$

where

- q(x) is an arbitrary positive function that is called weight function,
- F(x), $F(x,\bar{c})$ are given and generated functions respectively corresponding to input x_i , i=1,2,....n.

Eqs. (2.6-2.8) are called criterion at least square or sum square of rejection and Eqs. (2.7-2.9) are called criterion by Chebyshev or maximum rejection. Weight function q(x) allows more finely taking into account increased requirements to accuracy of approach $F(x,\bar{c})$ to F(x) in separate space from D.

Realization of synthesis problem with respect to Eqs.(2.6-2.9) come true by using methods of theory function approximation in combination with methods of optimization synthesis of mechanisms. Unknown function $F(x,\bar{c})$ is found by applying the theory of approximation and the best uniform approximation.

2.1.2 **Theory of Function Approximation**

Realization of design objective function by determining construction parameter $\bar{c}$ is accomplished by theory of function approximation methods. If design objective function is presented in the form of synthesis polynomial, by applying interpolation, square approximation and the best uniform approximation methods or their combinations one can find the values of mechanism's parameters which will generate the given function in the best possible manner. In case of assigning nonlinear design objective function, it is needed to perform linearization for obtaining linear system of equations.

Toward this end it is considered the way of defining Lagrange's factor. Applying superposition method, nonlinear equations are solved with respect to Lagrange's factor. Replacing construction parameters of non-linear design objective function through new coefficients with Lagrange's factor and carrying out corresponding transformations, it is received synthesis polynomial which includes new unknowns. Solving system of linear equations by using one of function approximation methods and calculating Lagrange's factor, values of the mechanism's construction parameters and error values of given function are defined. In this chapter design objective functions with one, two, three and four nonlinear terms is described.

2.1.2.1 **Interpolation**

The principle of interpolation theory is concluded in that the sought polynomial $F(x,\bar{c})$ in series indicated points have to take same value as a given function F(x) where the difference $F(x,\bar{c})$ - F(x) in the given points must convert to zero. (Fig 2.1)

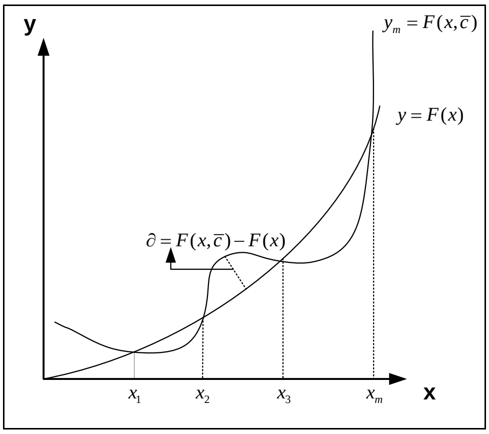


Figure 2.1 Interpolation Approximation

where,

$y = F(x)$ – given function,

$y_m = F(x,\bar{c})$ - generated function,

$\partial = F(x,\bar{c}) - F(x)$ - error between precision points

.

Let consider interpolation theory of summarizing polynomial. Assumption function $\{f_i(x)\}^n$, given and continuous functions and p are constant coefficients depending on construction parameters of mechanism. Expression in the form of,

$$F(x,\bar{c}) = \sum_{i=1}^{n} P_i f_i(x) \tag{2.8}$$

is called summarizing polynomial.

Particularly, if $f_1(x) = 1,\ f_2(x) = x,\ f_3(x) = x^2, \ldots\ldots\ldots\ldots\ldots,\ f_n(x) = x^{n-1}$ it is obtained usual algebraic polynomial with degree *n-1*.

If $\{f_i(x)\}_1^n$ is trigonometric system then the polynomial becomes trigonometric polynomial.

Let $\{f_i(x)\}_1^n$ is a linearly independent system in the form,

$$\sum_{i=1}^{n} P_i f_i(x) = 0 \ \rightarrow P_i = 0 \quad i = \overline{1,n} \tag{2.9}$$

Theorem: In order that the system $\{f_i(x)\}_1^n$ would be linearly independent it is necessary and sufficiently, that determinant

$$D(x_1, x_2, x_3, ..., x_n) = \begin{vmatrix} f_1(x_1) & f_2(x_1) & ..... & f_n(x_1) \\ f_1(x_2) & f_2(x_2) & ..... & f_n(x_2) \\ ..... & ..... & ..... & ..... \\ f_1(x_n) & f_2(x_n) & ..... & f_n(x_n) \end{vmatrix} \qquad (2.10)$$

identically must not equal to zero, when $x_1, x_2, ..., x_n$ take on every possible value from main interval.

Let $\{x_i\}_1^n$ is different number and $\{f_i\}_1^n$, given number. To be needed find $\{P_i\}_1^n$ on condition

$$F(x_i, \overline{c}) = F_i(x_i) \qquad i = \overline{1, n}$$

Possibility finding function $F(x_i, \overline{c})$ or solving the system Eq.(2.10) depends from that, to be whether distinguish from zero determinant $D(x_1, x_2, x_3, ..., x_n)$. The task Eq.(2.11) is interpolation problem for summarizing polynomial. For solving this task it is necessary linear independence of system $\{f_i(x)\}_1^n$, but for unique it is not sufficient. For a final solution of this task it is necessary the following definition:

If determinant $D(x_1, x_2, x_3, ..., x_n)$ equal to zero on condition of execution one of equality $x_i = x_k$ $(i \neq k)$, that system $\{f_k(x)\}_1^n$ is called Chebyshev system. For solving the interpolation task Eq.(2.10) it is necessary and sufficient, that system functions $\{f_i(x)\}_1^n$ will be Chebyshev system.

2.1.3 Path Generation Synthesis of Knotting Micromechanism

As mentioned in Section 1.2.4, the most tiring process of carpet manufacturing is weaving stage. For a prayer rug type carpet, an experienced weaver completes the whole carpet in three months by weaving 8 hours per day whereas this period rises over one year for “Taban” type carpet. Thus, in the robotization of the carpet weaving process, the most important part is the design of a fast and reliable weaving mechanism.

2.1.3.1 Path Generation Synthesis of R-R Dyad with Four Precision Points

For the design of a knotting mechanism, symmetric knot is used as a model. In this model, pile yarn, in desired color, is twisted around the two neighbor warps as shown in Figure 2.2.

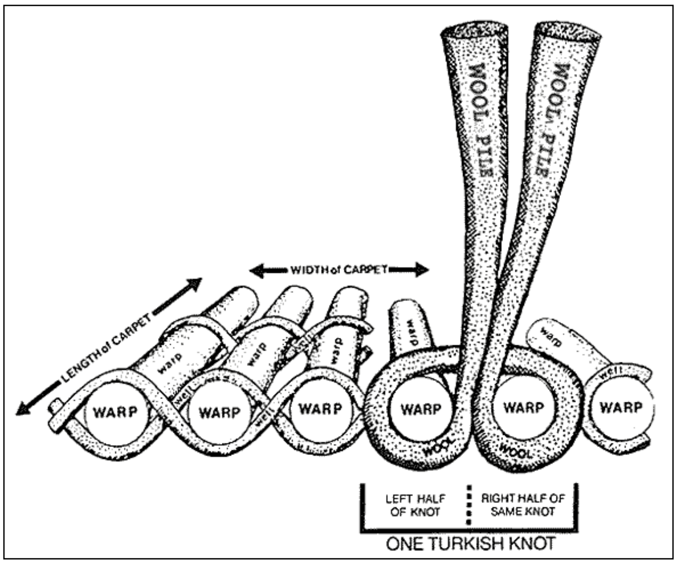


Figure 2.2 Illustration of Turkish knot on the warps.
(Source: Nejad Rugs)

As the knot is symmetrical, modeling only one side of motion will lead to the total process modeling. For this purpose, RR dyad actuated by two motors, each is located on the revolute joints, is selected. Each of these dyads is considered to have a gripper as their end effectors which hold the pile yarn. In order to accomplish the knotting process, these serial manipulators have to be designed by using dimensional synthesis. Moreover, the inverse task should be applied to perform the controls of the actuators. The layout drawing of RR dyad and the path of knot are given in Figure 2.3.

Dashed line represents the path of the pile around the warp yarns. Red points are the precision points of the synthesis function which are taken arbitrarily on the design path. a_1 and a_2 represents the link length of the serial arm, a_0 and θ_0 are the parameters locating base actuator of the serial manipulator. The aim of this problem is designing the construction parameters of the system (a_1, a_2, a_0, θ_0) by using given points (x_i, y_i) and given motor input (θ_{1i}) where i =1,2,3,4.

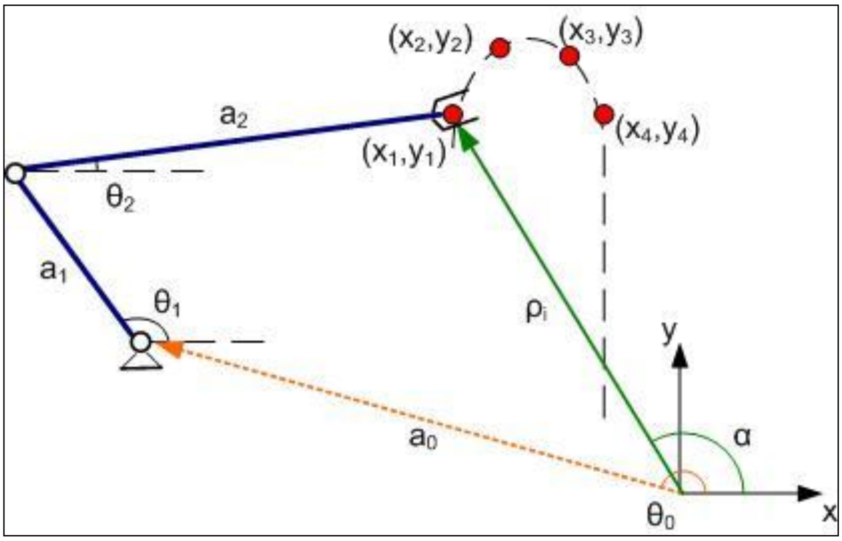


Figure 2.3 Layout drawing of Planar RR Knotting Mechanism with Kinematic Parameters

Loop closure equation:

$$\overline{O_0O_1} + \overline{O_1O_2} + \overline{O_2O_3} = \overline{O_0O_3} \tag{2.23}$$

The componentwise representation of Eq.(2.23) yields,

$$\rho_i.Cos(\alpha) = a_0.Cos(\theta_0) + a_1.Cos(\theta_1) + \tilde{a}_2.Cos(\theta_2) \tag{2.24}$$

$$\rho_i.Sin(\alpha) = a_0.Sin(\theta_0) + a_1.Sin(\theta_1) + \tilde{a}_2.Sin(\theta_2) \tag{2.25}$$

For the four precision point of the manipulator only the input parameter θ_1 is given. So the objective function of the system should not include the other input parameter θ_2.

Rearranging the eqns. (2.24 & 2.25) we will have,

$$\tilde{a}_2.Cos(\theta_2) = a_0.Cos(\theta_0) + a_1.Cos(\theta_1) - \rho_i.Cos(\alpha) \tag{2.26}$$

$$\tilde{a}_2.Sin(\theta_2) = a_0.Sin(\theta_0) + a_1.Sin(\theta_1) - \rho_i.Sin(\alpha) \tag{2.27}$$

By taking the square of both eqns. (2.26 & 2.27) and adding them yields,

$$\tilde{a}_2^2 = \rho_i^2 + a_0^2 + a_1^2 - 2a_0\rho_i Cos(\alpha)Cos(\theta_0) - 2a_1\rho_i Cos(\alpha)Cos(\theta_1) + 2a_0 a_1 Cos(\theta_0)Cos(\theta_1)$$
$$+ 2a_0 a_1 Sin(\theta_0)Sin(\theta_1) - 2a_0\rho_i Sin(\alpha)Sin(\theta_0) - 2a_1\rho_i Sin(\alpha)Sin(\theta_1) \tag{2.28}$$

Eq.(2.28) is the objective function of the system. By using this equation forward and inverse tasks of the system can be achived. However, for constructing synthesis equation, we will modify the equation.

Obviously, $2a_1\rho_i Sin(\alpha)Sin(\theta_1)$ and $2a_1\rho_i Cos(\alpha)Cos(\theta_1)$ includes the given parameters α and θ_1. In synthesis equation, it is required to form a construction-parameter-independent variable. For this purpose we will divide the whole equation with $2a_1$. Eq. (2.28) yields,

$$\frac{1}{2a_1}\tilde{a}_2^2 = \frac{1}{2a_1}\rho_i^2 + \frac{a_0^2 + a_1^2}{2a_1} - \frac{a_0 Cos(\theta_0)}{a_1}\rho_i Cos(\alpha) - Cos(\alpha)\rho_i Cos(\theta_1) + a_0 Cos(\theta_0)Cos(\theta_1)$$
$$+ a_0 Sin(\theta_0)Sin(\theta_1) - \frac{a_0 Sin(\theta_0)}{a_1}\rho_i Sin(\alpha) - \rho_i Sin(\alpha)Sin(\theta_1) \tag{2.29}$$

or equally,

$$\frac{1}{2a_1}\tilde{a}_2^2 = \frac{1}{2a_1}\rho_i^2 + \frac{a_0^2 + a_1^2}{2a_1} - \frac{a_0 Cos(\theta_0)}{a_1}\rho_i Cos(\alpha)$$
$$+ a_0 Cos(\theta_0)Cos(\theta_1) + a_0 Sin(\theta_0)Sin(\theta_1) \tag{2.30}$$
$$- \frac{a_0 Sin(\theta_0)}{a_1}\rho_i Sin(\alpha) - \rho_i Cos(\alpha - \theta_1)$$

Here $\tilde{a}_2^2$ represents the synthesized length of second link. By using actual and synthesized parameter we can construct a error function as,

$$\Delta_{a_2} = a_2 - \tilde{a}_2 \tag{2.31}$$

Multiplying the both sides of Eq. (2.31) with the conjugate of left hand side,

$$\Delta_{a_2}(a_2+\tilde{a}_2)=(a_2-\tilde{a}_2)+(a_2+\tilde{a}_2) \tag{2.32}$$

As the difference between $\tilde{a}_2$ and a_2 is so small we can assume that $a_2+\tilde{a}_2=2a_2$. Substituting into Eq. (2.32) yields,

$$\Delta_{a_2}=\frac{({a^2}_2-\tilde{a}_2^2)}{2a_2} \tag{2.33}$$

For the precision points the error function will be zero so the objective function yields,

$$\Delta q=({a^2}_2-\tilde{a}_2^2)=0 \tag{2.34}$$

Substituting Eq.(2.30) into (2.34) yields,

$$\begin{aligned}\Delta q=&\frac{1}{2a_1}\rho_i^2+\frac{a_0^2+a_1^2-{a^2}_2}{2a_1}-\frac{a_0Cos(\theta_0)}{a_1}\rho_iCos(\alpha)\\&+a_0Cos(\theta_0)Cos(\theta_1)+a_0Sin(\theta_0)Sin(\theta_1)\\&-\frac{a_0Sin(\theta_0)}{a_1}\rho_iSin(\alpha)-\rho_iCos(\alpha-\theta_1)=0\end{aligned} \tag{2.35}$$

For the sake of simplicity, Eq.(2.35) can be written in the polynomial form as,

$$P_0f_0+P_1f_1+P_2f_2+P_3f_3+P_4f_4+P_5f_5-F=0 \tag{2.36}$$

where

$$\begin{aligned}&P_0=\frac{a_0^2+a_1^2-{a^2}_2}{2a_1},\ f_0=1,\ P_1=\frac{1}{2a_1},\ f_1=\rho_i^2,\ P_2=\frac{a_0Cos(\theta_0)}{a_1},\ f_2=-\rho_iCos(\alpha),\\&P_3=\frac{a_0Sin(\theta_0)}{a_1},\ f_3=-\rho_iSin(\alpha),\ P_4=a_0Cos(\theta_0),\ f_4=Cos(\theta_1)\\&P_5=a_0Sin(\theta_0),\ f_5=Sin(\theta_1),\ F=\rho_iCos(\alpha-\theta_1)\end{aligned}$$

In Eq.(2.36) P_i include only the construction (synthesis) parameters whereas f_i include only the given parameters. In fact the problem has four synthesis parameters (a_0, a_1, a_2, θ_0) with four independent precision points ($\rho_i, \alpha_i \; where \, i = 1,2,3,4$). However Eq.(2.36) include six unknown parameters where two of them are non-linear as,

$$\begin{aligned} P_2 &= 2P_1P_4 \\ P_3 &= 2P_1P_5 \end{aligned} \tag{2.37}$$

In this case, we have four known poses and six unknown parameters. For solving this problem, it would be useful to introduce the construction parameters as, $P_i = l_i + \lambda_1 m_i + \lambda_2 n_i$, exceptionally, $P_2 = \lambda_2$ and $P_3 = \lambda_3$.

So Eq. (2.36)yields,

$$\begin{aligned} &\left(l_0 + \lambda_1 m_0 + \lambda_2 n_0\right) f_0 + \left(l_1 + \lambda_1 m_1 + \lambda_2 n_1\right) f_1 + \left(l_4 + \lambda_1 m_4 + \lambda_2 n_4\right) f_4 \\ &+ \left(l_5 + \lambda_1 m_5 + \lambda_2 n_5\right) f_5 = F - 2\lambda_1 f_2 - 2\lambda_2 f_3 \end{aligned} \tag{2.38}$$

Seperating the Eq(2.38) depending on the virtual parts and real part,

$$\begin{aligned} &l_0 f_{0(i)} + l_1 f_{1(i)} + l_4 f_{4(i)} + l_5 f_{5(i)} = F_{(i)} \\ &m_0 f_{0(i)} + m_1 f_{1(i)} + m_4 f_{4(i)} + m_5 f_{5(i)} = -2 f_{2(i)} \\ &n_0 f_{0(i)} + n_1 f_{1(i)} + n_4 f_{4(i)} + n_5 f_{5(i)} = -2 f_{3(i)} \end{aligned} \tag{2.39}$$

where i=1,2,3,4.

So in Eq Set (2.39) we have 12 unknown parameters ($l_0, l_1, l_4, l_5, m_0, m_1, m_4, m_5, n_0, n_1, n_4, n_5$) in 12 linear equation. As the equations are linear, the solution of (2.39) could be find by matrix method. Eq. (2.39) can be written in the matrix form,

$$\begin{pmatrix} f_{0(1)} & f_{1(1)} & f_{4(1)} & f_{5(1)} \\ f_{0(2)} & f_{1(2)} & f_{4(2)} & f_{5(2)} \\ f_{0(3)} & f_{1(3)} & f_{4(3)} & f_{5(3)} \\ f_{0(4)} & f_{1(4)} & f_{4(4)} & f_{5(4)} \end{pmatrix} \begin{pmatrix} l_0 \\ l_1 \\ l_4 \\ l_5 \end{pmatrix} = \begin{pmatrix} F_{(1)} \\ F_{(2)} \\ F_{(3)} \\ F_{(4)} \end{pmatrix}$$

$$\begin{pmatrix} f_{0(1)} & f_{1(1)} & f_{4(1)} & f_{5(1)} \\ f_{0(2)} & f_{1(2)} & f_{4(2)} & f_{5(2)} \\ f_{0(3)} & f_{1(3)} & f_{4(3)} & f_{5(3)} \\ f_{0(4)} & f_{1(4)} & f_{4(4)} & f_{5(4)} \end{pmatrix} \begin{pmatrix} m_0 \\ m_1 \\ m_4 \\ m_5 \end{pmatrix} = \begin{pmatrix} -2f_{2(1)} \\ -2f_{2(2)} \\ -2f_{2(3)} \\ -2f_{2(4)} \end{pmatrix} \tag{2.40}$$

$$\begin{pmatrix} f_{0(1)} & f_{1(1)} & f_{4(1)} & f_{5(1)} \\ f_{0(2)} & f_{1(2)} & f_{4(2)} & f_{5(2)} \\ f_{0(3)} & f_{1(3)} & f_{4(3)} & f_{5(3)} \\ f_{0(4)} & f_{1(4)} & f_{4(4)} & f_{5(4)} \end{pmatrix} \begin{pmatrix} n_0 \\ n_1 \\ n_4 \\ n_5 \end{pmatrix} = \begin{pmatrix} -2f_{3(1)} \\ -2f_{3(2)} \\ -2f_{3(3)} \\ -2f_{3(4)} \end{pmatrix}$$

By taking the inverse of 4x4 matrix and multiplying with left-hand matrix, the values of unknown parameters can be calculated.

Despite calculating 12 unknown parameters, the values of λ_1 and λ_2 are still unknown. Substituting $P_i=l_i+\lambda_1 m_i+\lambda_2 n_i$, $P_2=\lambda_1$, $P_2=\lambda_2$ into Eq. Set (2.37) with calculated parameters,

$$\lambda_1 = (l_1+\lambda_1 m_1+\lambda_2 n_1)(l_4+\lambda_1 m_4+\lambda_2 n_4) \tag{2.41}$$

$$\lambda_2 = (l_1+\lambda_1 m_1+\lambda_2 n_1)(l_5+\lambda_1 m_5+\lambda_2 n_5) \tag{2.42}$$

Rearranging the Eq.s(2.41 & 2.42),

$$\lambda_1^2(m_1m_4)+\lambda_2^2(n_1n_4)+\lambda_1\lambda_2(m_1n_4+m_4n_1)+\lambda_1(l_1m_4+l_4m_1-\frac{1}{2})+\lambda_2(l_1n_4+l_4n_1)+l_1l_4=0 \tag{2.43}$$

$$\lambda_1^2(m_1m_5)+\lambda_2^2(n_1n_5)+\lambda_1\lambda_2(m_1n_5+m_5n_1)+\lambda_2(l_1n_5+l_5n_1-\frac{1}{2})+\lambda_1(m_1l_5+m_5l_1)+l_1l_5=0 \tag{2.44}$$

For the solution, Eq.(2.44) will be multiplied with $-n_1n_4/n_1n_5$ and add it to Eq.(2.43) in order to eliminate λ_2^2 . Equation becomes,

$$A_1\lambda_1^2 + A_2\lambda_1\lambda_2 + A_3\lambda_1 + A_4\lambda_2 + A_5 = 0 \tag{2.45}$$

where,

$$A_1 = m_1 m_4 - \frac{m_1 m_5 n_4}{n_5}$$
$$A_2 = m_4 n_1 - \frac{m_5 n_1 n_4}{n_5}$$
$$A_3 = l_4 m_1 + l_1 m_4 - \frac{l_5 m_1 n_4}{n_5} - \frac{l_1 m_5 n_4}{n_5} - \frac{1}{2}$$
$$A_4 = l_4 n_1 + \frac{n_4}{2n_5} - \frac{l_5 n_1 n_4}{n_5}$$
$$A_5 = l_1 l_4 - \frac{l_1 l_5 n_4}{n_5}$$

From Eq (2.45) λ_2 yields,

$$\lambda_2 = \frac{A_1\lambda_1^2 + A_3\lambda_1 + A_5}{-(A_4 + A_2\lambda_1)} \tag{2.46}$$

Substituting λ_2 into Eq. (2.43) we will have third order equation with one unknown parameter (λ_1) is acquired as the constant of λ_1^4 becomes zero after substituting the values. As the equation becomes third order it has an analytical solution. As the value of λ_1 is known it is easy to calculate λ_2 from Eq. (2.46).

Finally, by substituting λ_1 and λ_2 into, the values $P_i = l_i + \lambda_1 m_i + \lambda_2 n_i$ of P_i, where i=1,2,3,4 , can be calculated.

2.2. Design of Weaving Mechanism by Using Cam Systems

2.2.1 Cam Systems

Cam is a mechanical component that is used to drive the follower through a desired motion by direct contact. A cam system is, generally, a single-degree of freedom device which is driven by a known input motion, usually a shaft rotating at a constant speed. It is intended to produce a certain desired periodic output motion of the follower. These systems are simple, inexpensive and reliable. Thus, cam systems are widely used in modern machinery.

For the sake of clarity, it will be useful to give some basic terminology about cam and its characteristic properties.

- *Cam profile:* Cam profile is usually defined as projection of a cam on to a plane perpendicular to the axis of rotation of the cam.
- *Follower:* A cam follower is the part of a cam system which transmits the motion prescribed by cam profile. Depending on shape of the follower, cam systems can be classified in four different types.
    - *Flat-face follower*
    - *Roller follower*
    - Spherical follower
    - *Knife-edge follower*
- *Rise*: This term is used for part of the cam profile where the follower moves away from the center of rotation. The maximum rise is called lift.
- *Fall*: The fall of a cam is defined as the section of a cam profile where the follower moves toward the center of rotation.
- *Dwell*: Dwell is the part of the cam profile which describes the period when the follower is stationary.

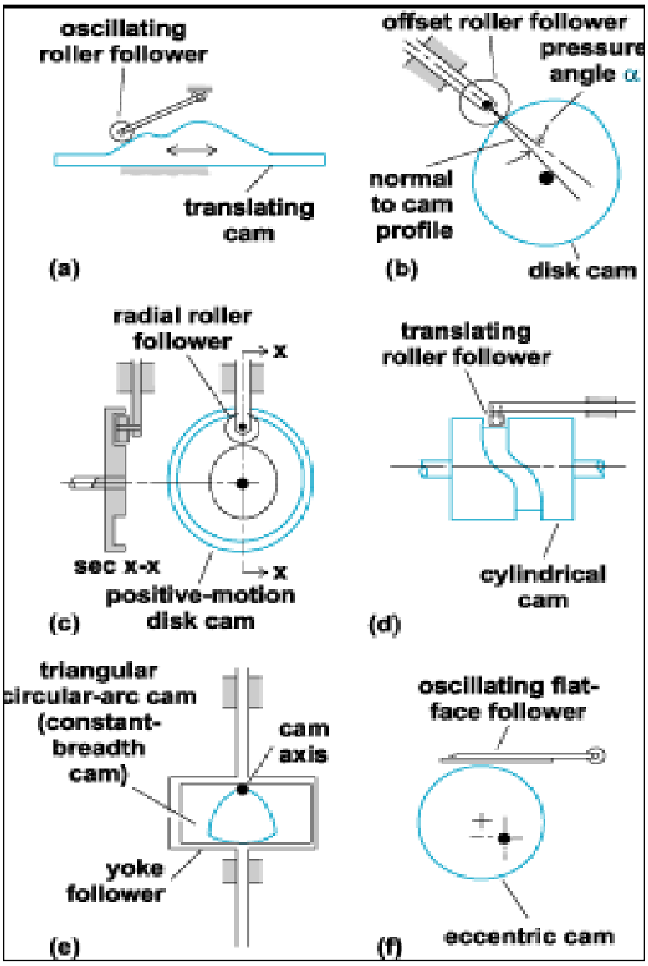


Figure 2.4 Follower and Cam Systems
(Source: Content Answer)

2.2.2 Displacement Diagrams

The follower executes a series of motion during the rotation of the cam through one cycle input. The motion of the follower can be shown in a displacement diagram. However, this term is misleading for conical, spherical, cylindrical or 3-D cam systems. In general, cam profile is the shape that causes the follower motion. There are four different types of cam system based on the shape of the cam:

- Plate Cam
- Wedge Cam
- Cylindrical or Barrel Cam
- End or Face Cam

Displacement diagrams are used to represent the motion of the follower. In such a diagram, abscissa represents the one cycle of the input whereas ordinate represents the displacement of the follower (Figure 2.5).

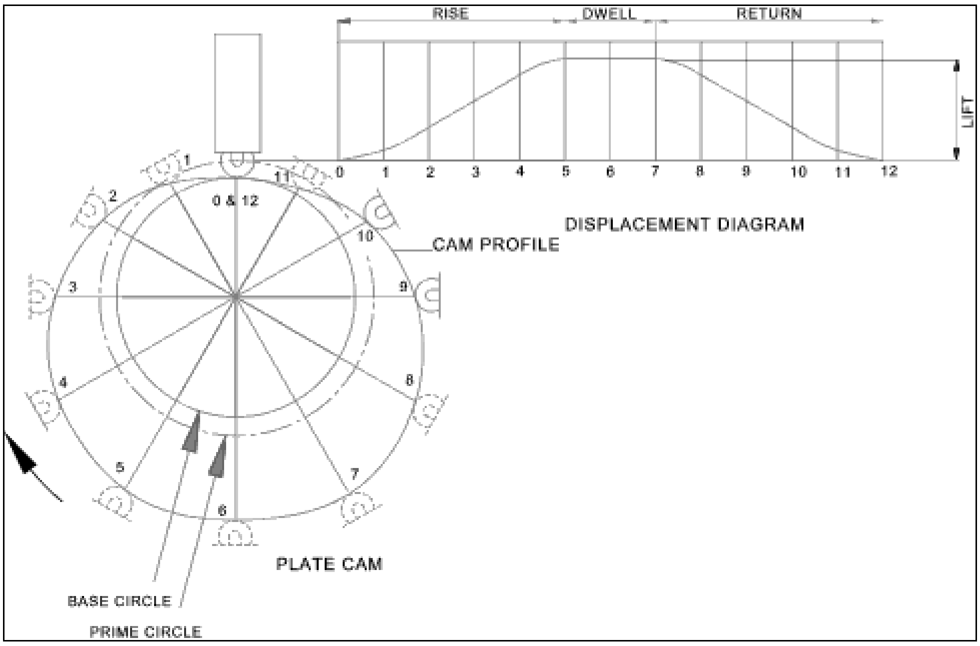


Figure 2.5 Displacement Diagram of a cam and follower
(Source: Roymech)

The shape of the displacement diagram represents the motion of the follower. This shape usually determined by the displacement requirements of the system. However, designer has to consider the system dynamics include pressure angle, velocity and acceleration of the follower.

There are variety of choices for follower motion, those defines the total lift or the placement and duration of dwells. Keystone in cam design is the choice of the right form of motion which is most suitable for the system requirements. Once, the motion is chosen the displacement could be constructed precisely.

In general, four different motion model is used in cam design. Each of them has different dynamical and graphical properties.

- *Uniform Motion:* The most basic motion model is uniform motion. This model is constructed with a constant slope straight line. As the slope is constant, for constant input speed, the velocity of the follower is also constant. This motion is not useful for the full lift due to the corners produced at the transition sections. It is often used between curved sections in the diagrams.
- *Modified Uniform Motion:* Due to the corners produced at transition sections, instead of constant velocity motion, parabolic or constant acceleration motion, commonly used in cam motion models.

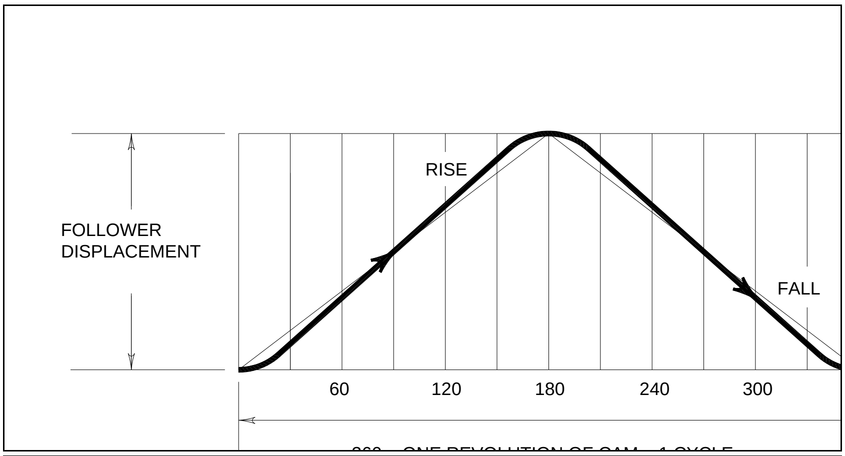


Figure 2.6 Modified Uniform Motion
(Source: Cad Resources)

In this system, the acceleration or the deceleration of the follower remains constant. Parabolic motion provides for the minimum acceleration possible for a given displacement. Construction of a parabolic motion is given in Figure 2.7.

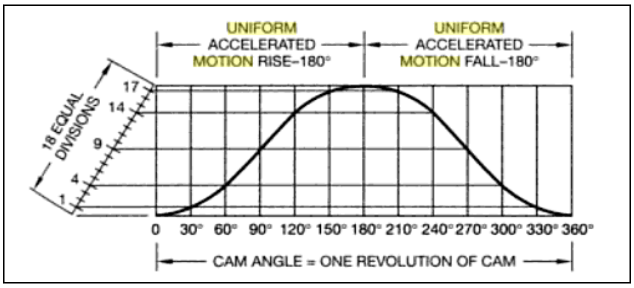


Figure 2.7 Graphical Construction of Parabolic Motion
(Source: Engineering Drawing and Design)

- *<u>Simple Harmonic Motion</u>:* The projection of a point moving along the circumference of a circle on to the circle diameter as the circle radius moves with constant velocity is known as simple harmonic motion. The simple harmonic model is used for uniformly changing velocity with some jerk (third derivative of displacement) of the follower at the start and finish of the motion.

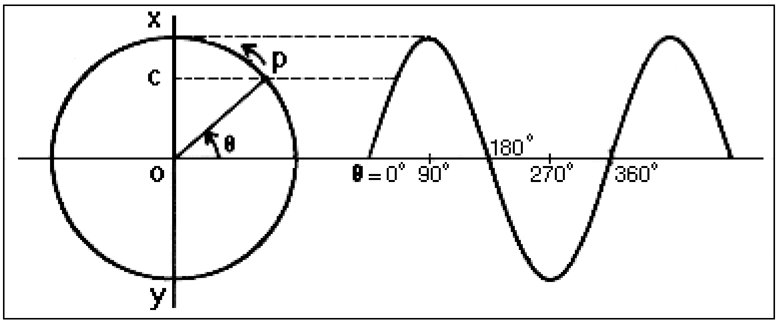


Figure 2.8 Simple harmonic Motion Displacement Diagram
(Source: SFU)

The displacement diagram for simple harmonic motion is given in Figure 2.8. For the construction of the diagram, a semicircle is used which has a diameter equal to total rise of the follower (L). The semicircle and abscissa are divided into an equal number of parts where abscissa represents the cam rotation; ordinate represents the displacement of the follower. Then, the points on abscissa and semicircle matched on the diagram. Parabola gets through these points is the graphical representation of the simple harmonic motion.

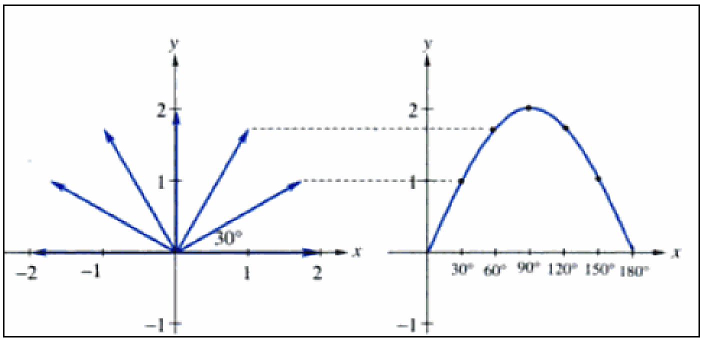


Figure 2.9 Curve Generation of Simple Harmonic Motion
(Source: Technical Mathematics)

In Figure 2.9 as the generating radius moves through the angle φ, the cam rotates through the angle θ and the displacement of the follower is given as S. Mathematically, these motions could be represented by,

$$S = \frac{L}{2} - \frac{L}{2} Cos\theta \tag{2.47}$$

As the total cam rotation is given as β and the total radius moved by the generation radius is π ;

$$\frac{\phi}{\pi} = \frac{\theta}{\beta} \qquad or \qquad \phi = \frac{\theta\pi}{\beta} \tag{2.48}$$

Substituting (2.48) into (2.47) yields,

$$S = \frac{L}{2(1 - Cos\frac{\theta\pi}{\beta})} \tag{2.49}$$

The first and second derivatives of equation (2.49) will give the velocity and acceleration of the system respectively,

$$V = \left(\frac{\pi L}{2\beta} Sin \frac{\pi\theta}{\beta} \right) \omega \qquad where \qquad \omega = \frac{d\theta}{dt} \tag{2.50}$$

$$A = \left(\frac{\pi^2 L}{2\beta^2} Cos \frac{\pi\theta}{\beta} \right) \omega^2 \tag{2.51}$$

- *Cycloidal Motion:* For modeling, a jerk-free motion of follower with good high speed characteristic, cycloidal motion model is widely used. A cycloid is defined as the locus of point on a rolling circle along a straight line.

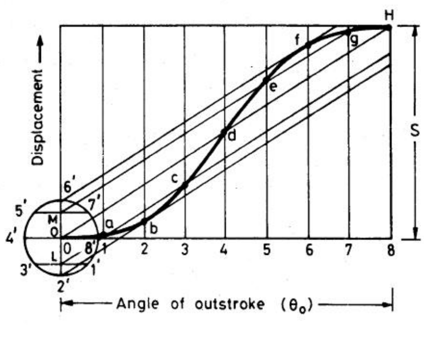


Figure 2.10 Cycloidal Motion Model
(Source: Theory of Machines and Mechanisms)

The graphical representation of a cycloidal displacement diagram is given in Figure 2.10. The subordinate of this diagram represents the rolling of a circle, which has a radius L / 2π (L-total rise) along y axis. In diagram, the trace of point P is shown which is initially located at the origin of the diagram. As the generating circle rolls along y axis, projection of P constructs parabolas given.

Denoting;

Φ – Rotation of generating circle

θ – Cam rotation

β – Total motion of a cam or cycloidal

Thus, displacement of the follower (s) yields;

$$S = R.\emptyset - R.Sin\emptyset = R(\emptyset - Sin\emptyset) \tag{2.52}$$

As the follower has a total lift during a complete revolution of generating circle;

$$\emptyset = 2\pi\theta/\beta \tag{2.53}$$

Substituting (2.52) into (2.53) yields;

$$S = \frac{L\theta}{S} - \frac{L}{2\pi} Sin \frac{2\pi\theta}{\beta} \tag{2.54}$$

Differentiating equation (2.54) with respect to time gives the velocity and the acceleration of the follower;

$$\vartheta = \frac{L}{\beta\left(1 - Cos\frac{2\pi\theta}{\beta}\right)w} \tag{2.55}$$

$$a = \frac{2\pi L}{\beta^2\left(Sin\frac{2\pi\theta}{\beta}\right)w^2} \tag{2.56}$$

2.2.3 Design of Weaver System with Cam and Follower Mechanisms

The end effector of the arm, called as the weaver, is a mechanical system for tying a symmetrical knot. The process of weaver can be defined in 4 steps as, preparing the pile for knotting, getting some workspace by opening up the warp threads, knotting phase and grasping the knotted pile. After these processes, the arm will push all the system downwards and release the pile. For the whole process by using one motor and in the right order, cyclogram is figured as shown in Figure 2.11. In the cyclogram all steps defines the motion of cams and gears which are related to the motion of the related mechanisms such as side and center grippers' sley motion and pile handler mechanisms.

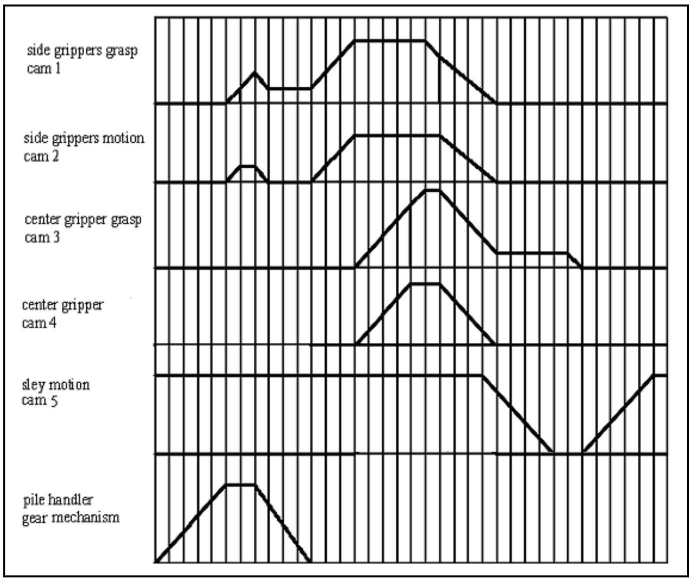


Figure 2.11 Cyclogram of Weaving Process

Before starting the knotting process the pile with the color in order must be prepared for the weaver. The mechanisms for preparation of the pile are shown in Figure 2.12.

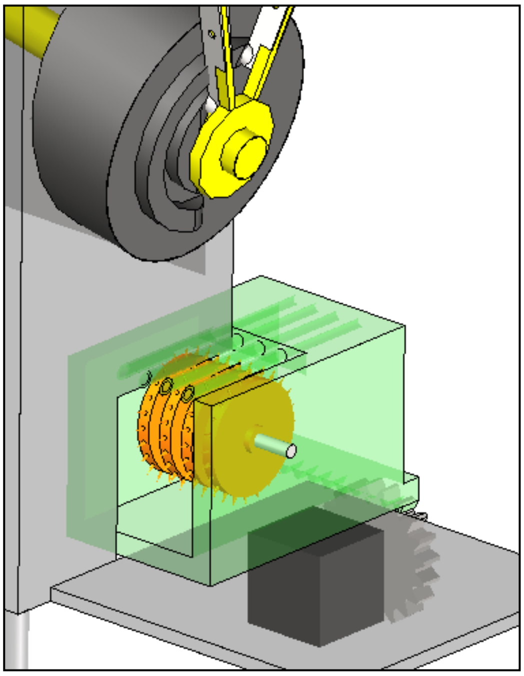


Figure 2.12 System for preparing the pile

Preparation of the pile for weaving starts with the selection of the color. The data comes to the stepper motor and the tube of the selected color come inline with the handler. The input of the handler is driven by the handling cam, the fifth one in the cyclogram. During its full rotation the handler grasps a pile from the desired tube then a cutter will operate to cut the unnecessary part of the yarn then takes the pile in front of the side grippers whose motions are driven by side gripper motion and side gripper grasp cams which are cam 2 and cam 1 in the cyclogram. Now the side gripper's grasp the pile from both ends then pull back a little so the handler continues to turn and stops at its start point. The grippers and the pile handler are shown in Figure 2.13.

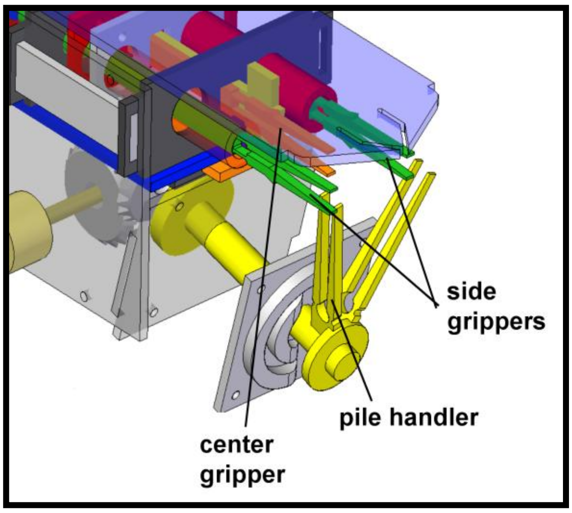


Figure 2.13 Grippers

For opening up some space the system shown in Figure 2.14. is attached to the side gripper's motion cam. While the system goes forward as shown in figure. Two of the warp threads get in to the slots of the system and the others are sided to the sides of the system

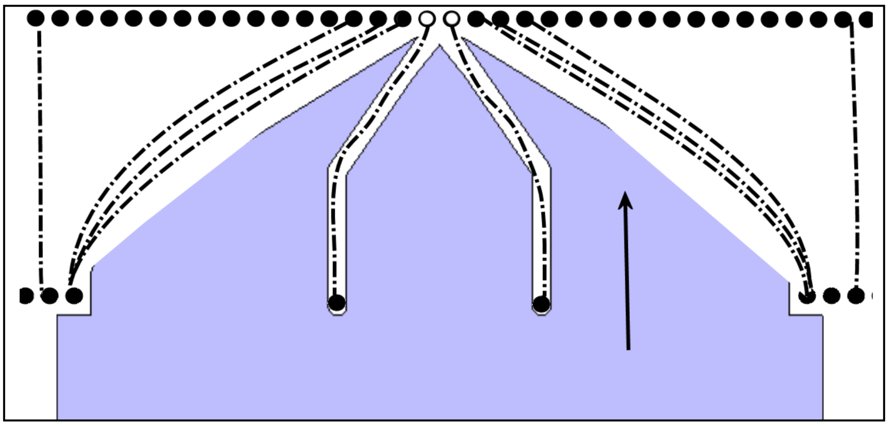


Figure 2.14 Mechanism for holding the warps

After taking the pile for side grippers to make the knot cam 1 and cam 2 is used. They are working simultaneously for the motion and asynchronous for the grasping. As the motion of the pile at the side grippers must be both linear and rotary a screw system is used as shown in Figure 2.15.

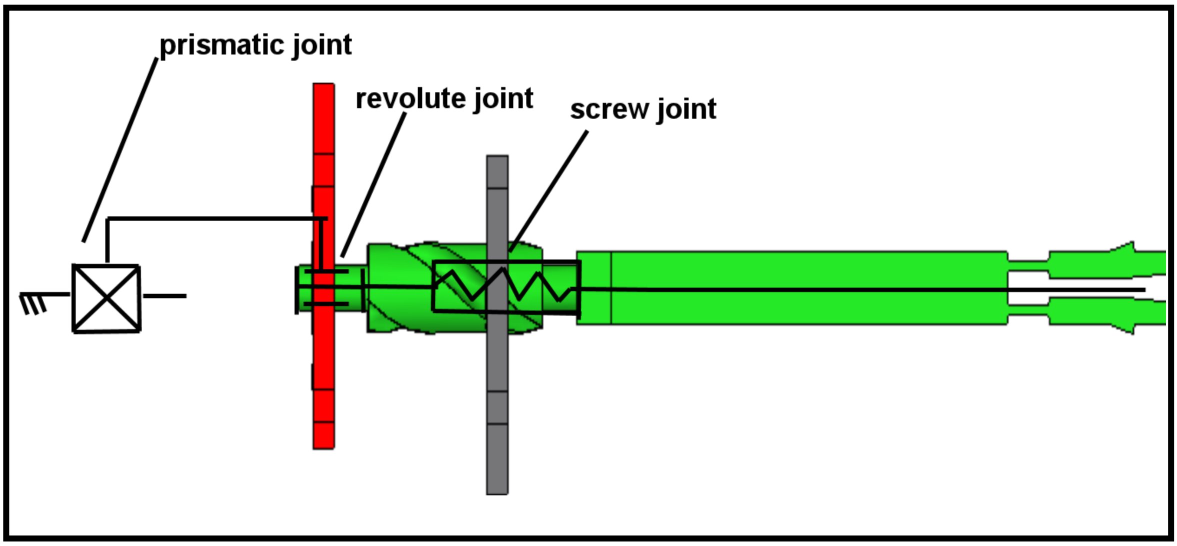


Figure 2.15 Screw system for side grippers

After the pile makes a cross at the center gripper moves with the motion of cam 3 and cam 4 and it grasps the pile by the movement of only cam 3.

After the gripping of center gripper, side grippers release the pile by the movement of cam 1 then the sley mechanism pushes down the knot. Finally, the center gripper releases the pile and the mechanism gets to its first position where the cam has returned 360 degrees. The general view of the designed weaver system with cam and gear mechanisms are shown in Figure 2.16

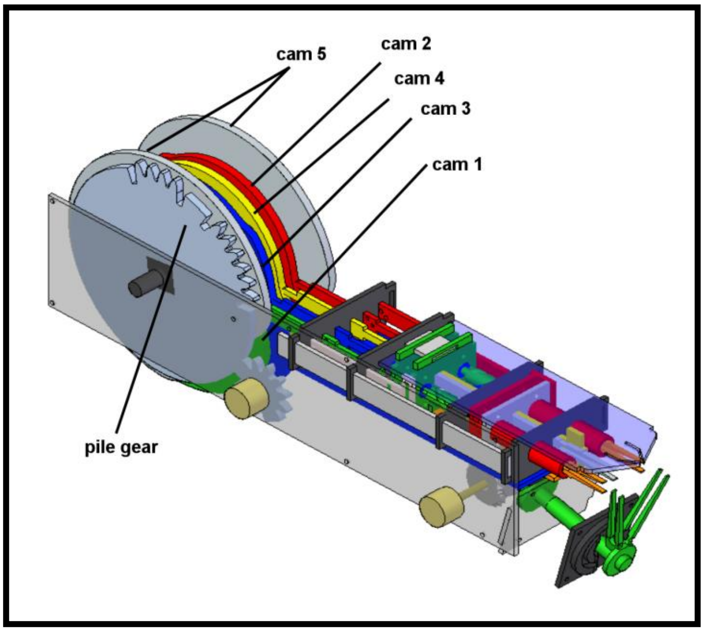


Figure 2.16 General view of cams

CHAPTER 3

DESIGN OF FULLY AUTOMATED CARPET LOOM

As it is mentioned in Section 1.2.4, weaving process inludes three basic stages: wefting, knotting and hammering. In previous section, some alternative designs for knotting operation were introduced. In this section, robotization of the remaining processes and the design considerations for the general carpet robot chasis will be given.

3.1 Design of Warp Tension and Spacing System

Knotting process is the basis of carpet manufacturing. In order to automate the knotting operation, it is important to apply appropriate tension to the warps and provide the suitable space between neighbor warps. In addition, these processes should be completed with wefting and hammering processes in order to manufacture a full carpet.

Figure 3.1 Warp yarns attached on a traditional loom
(Source: Ginger Bread Snow Flakes)

In knotting operation, applying appropriate tension to the warps is the keystone of the whole process. Basically, appropriatness depends upon the thickness of the warps (Figure 3.1). As the warps get thinner and longer under the tensile force, more knots could be tighten on unit area. In addition, after the carpet is detached, warps tend to shrink, which applies a compressive force on the knots, results in smoother appearance (Figure 3.2).

Figure 3.2 Warp and Weft Threads on a Carpet

Some alternative tension-applied warps are attached on the several looms for weaving operation. For the quality aspects, alternatives are discussed with exprienced weavers. As the strength and manufacturing considerations are taken into account with the quality requirements, appropriate tension of a single warp is decided as 15 N.

Generally, in traditional carpet looms, tension of the warps are provided by a hexagonal-slotted cylinder (Figure 3.3). In past, these cylinders were widely made of wood where the deflection problem leads to non-uniform tension over the warps. After the usage of metals instead of wood; deflection, and uniform tension problem has been solved relatively.

Figure 3.3 Hexagonal Slotted Cylinder

Recently, in carpet workshops, before the weaving stage, warps are attached on two bars (Figure 3.4).

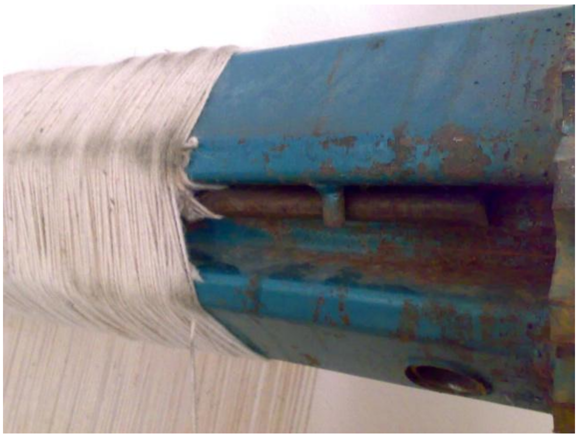


Figure 3.4 Attachment bars

These bars are placed into the slots on the cylinders. Appropriate tension of the warps are provided by applying torque on the cylinders with the help of a lever. Then the cylinders are held in the desired position by a locking system (Figure 3.5).

Figure 3.5 Locking System

When the weaver completes a portion of the carpet, cylinders are unlocked and the woven part twisted on the bottom cylinder (Figure 3.6).

Figure 3.6 Woven part twisted on the bottom cylinder

Basically, the design of this study based on the same logic mentioned above. Instead of the lever, actuation of the cylinders are provided by a motor-reducer system. Reducers are not only used for torque reducing but also as a locking system. In order to reduce the material and manufacturing costs, minimum diameter and thickness of the cylinders should be specified for the deflection requirements.

First of all, in the design stage of the cylinders, it is important to define the minimum diameter and thickness. As discussed earlier, tension of a single warp is defined as 15N. So the design of the cylinders turns into a basic strength problem. Schematic representation of the problem is given in Figure 3.7.

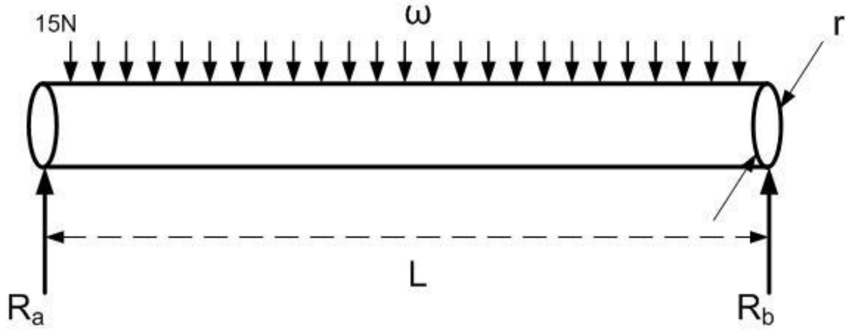


Figure 3.7 Schematic representation of the strength problem of cylinders

Mainly, there are two constraints in the design problem: maximum deflection that occurs in the cylinders and eccentricity of each cylinder with the bearings.

Generally, it is assumed that the slope of a shaft centerline with respect to a rolling-bearing outer ring centerline ought to be less than 0,001 rad for cylindrical and 0,0005 rad for tapered roller bearings. Similarly, it should be less than 0.004 rad for deep-groove roller bearings. Also for the uniform tension distribution over the warps, the maximum deflection of the cylinders should not exceed 1mm.

Referring to Figure 9, reaction forces occur in the support bearing will be given as;

$$R_1 = R_2 = \frac{\omega . l}{2} \tag{3.1}$$

where ω represents the load distribution on the cylinder (N/m) and l represents the length of the cylinder. Bending force along the cross-section will be,

$$V = \frac{\omega.l}{2} - \omega.x \qquad (3.2)$$

Substituting the radius of curvature formula into Eq.(3.2) and integrate the bending force with respect to boundary conditions, yields to deflection equation;

$$y = \frac{\omega.x}{24.E.I}(2.l.x^2 - x^3 - l^3) \qquad (3.3)$$

For the uniform load distribution on the uniform cross-section, the maximum deflection occurs in the middle of the cylinder which is given as,

$$y_{\max} = -\frac{5.\omega.l^4}{384.E.I} \qquad (3.4)$$

Differentiating the deflection for the boundary conditions of the shaft yields to slope of the cylinder,

$$\theta_A = -\frac{\omega.l^3}{24.E.I} \quad @\, x = 0 \qquad (3.5)$$

Load distribution affecting on the cylinder will be computed by,

$$\omega = \frac{\tau.n}{l} \qquad 3.6)$$

where

T- Tension in a single warp yarn

n- Total number of warps twisted on the cylinder

l- Length of the cylinder

Substituting Eq.(3.6) into (3.5) yields to design equation,

$$\theta_A = -\frac{\tau.n.l^2}{24.E.I} \qquad \text{nnn}(3.7)$$

For deep groove ball bearing supports, the slope found in Eq.(3.7) should not exceed 0,004 rad for assembly considerations. Variety of maximum deflection values are given in Table 3.1 for different thickness and diameter values which satisfies the assembly requirement. Second column of Table 3.1, denoted as $R_{outer(min)}$, represents the minimum outer diameter of the tube which satisfies the slope requirement.

Table 3.1 – Variety of maximum deflections (for Steel)

R_{inner} [mm]	$R_{outer(min)}$ [mm]	$R_{outer(chosen)}$ [mm]	y_{max} [mm]
50	51,69	60	0,037
75	75,52	85	0,012
100	100,22	110	0,005
125	125,12	135	0,0028
150	150,066	160	0,0016

As it is observed, the deflection and the slope requirements are easily satisfied by the selected dimensions. However, the space requirements for the slot and the length of the warps twisted on the cylinders narrows the dimensional selection where the inner diameter of the cylinder should be at least 100 mm.

On the other hand, cold drawn steel tubes generally have low surface quality and dimensional tolerances above 80mm. diameter. A variety of circular hollow profiles are inspected with different inner diameters and thicknesses. During inspection, a circular tube satisfied all the dimensional and strength requirements with a diameter of 140 mm and thickness of 5mm. Applying Eq.(3.4) for the given values, maximum deflection yields 0,0025 mm. and slope is 0,000052 (weight of the cylinder neglected). After these specifications, the design of the cylinders are given in Figure 3.8.

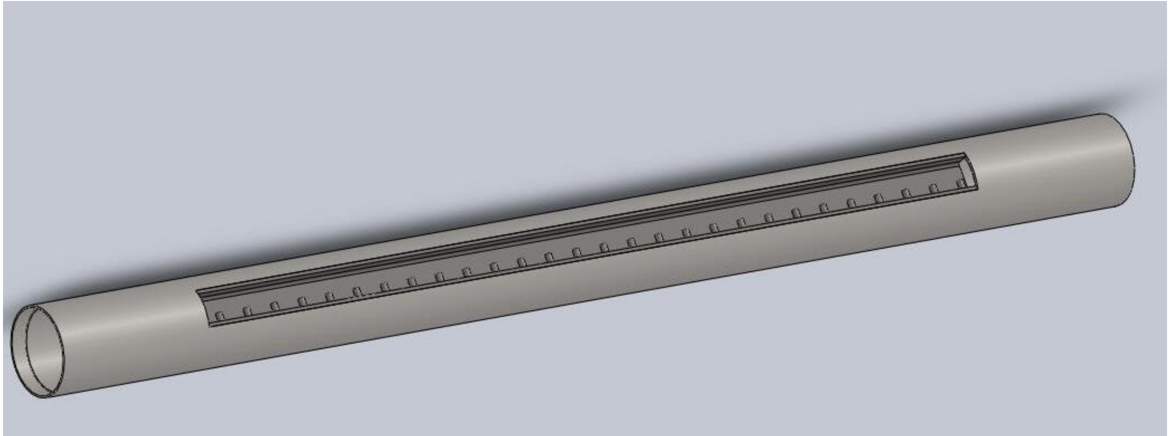


Figure 3.8 Cylinder design of carpet loom

These cylinders are supported by two UCF 207 type bearings which were selected from the bearing catalogue with respect to dynamic loading rate.

The required torque for actuating the system will be calculated by,

$$M = \sum_{i=1}^{600} F_i . d_i \tag{3.8}$$

where i represents the number of the warp yarn and d represents the normal distance of tensional force of each warp, F, from the center of rotation (Figure 3.9).

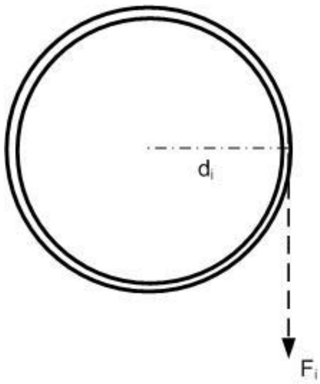


Figure 3.9 Schematic representation of required torque problem

Substuting the values of F = 15 N and d = 0,07 m. into Eq.(3.8) , resultant torque will be 630 N.m. The working torque of step motors, used as actuators, is about 7 N.m where a reducer which has 1:100 reduction ratio, should be sufficient for the torque reduction. Mounting the motor-reducer system on the cylinders, three cylinders are assembled as given in Figure 3.10.

Figure 3.10 Assembly of the cylinders with the chasis

Another important aspect for the robotization of knotting operation is to provide uniform spacing between two warps. During knotting operation, as mentioned before, weaver mechanisms pulled neighbor warp yarns where the knot would be tighten. If the space between two warps is not uniform, manipulators should knot the wrong couple of warps which results in defects in carpet.

For this purpose, despite the fact that two cylinders are widely used in traditional carpet looms, an additional cylinder used as shown in Figure 3.11. There are circular slots on this cylinder with a spacing of 2 mm (Fig.3.11).

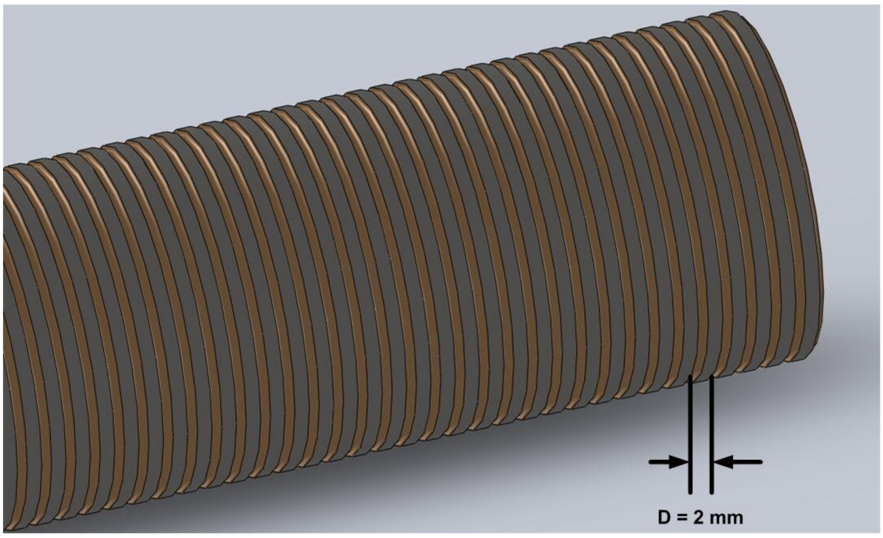


Figure 3.11 "Spacer" Cylinder

Warps are guided by these slots during their slip over this cylinder while the weaving process. In two cylinder carpet looms, as woven part twisted around itself on the bottom cylinder some defects and errors occur after carpet detached from the loom. Another advantage of three cylinders is that, the woven part remains between two bottom cylinders without being twisted.

3.2 Design of Wefting Mechanism

Another design consideration in robotization of carpet weaving is designing a mechanical system that is capable of imitating the wefting process. As discussed in Section 1.2.4, weft yarns are used as the boundaries of the knots on the carpet (Figure 3.12).

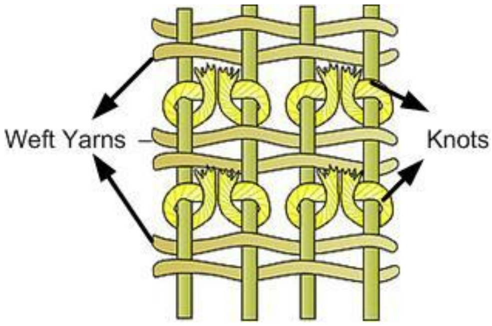


Figure 3.12 Weft yarns on a carpet
(Source: Wikipedia)

This process basically based on crossing the warp yarns in the desired order while weft yarn passed through them.
In traditional looms, this process is accomplished with a bar, which seperates odd and even warps, and a row of special knot, tighten before the woven part (Figure 3.13).

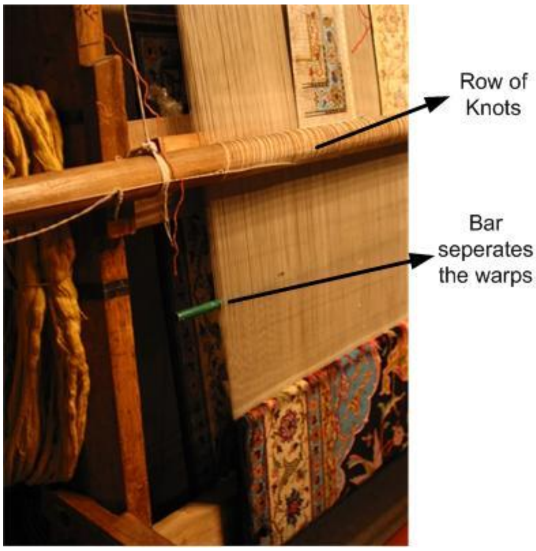


Figure 3.13 Knot and bar system for wefting process

Weaver, firstly brings the even warps forward where odd warps stay at the back, by pulling the bar downward [(igure 3.14).

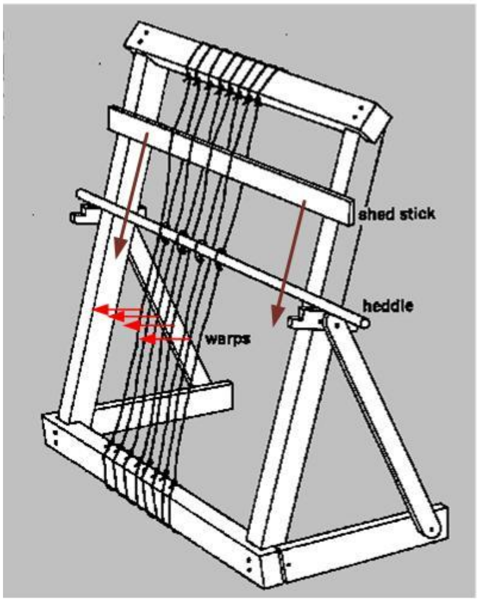


Figure 3.14 First Stage of Wefting Process

(Source : Pandiths)

Then, through the separated warps, weft yarn is passed (Figure 3.15). This warp pulled down tighten knots and squeezed by hammering process which will be discussed in the latter section. After hammering process, by pushing the bar upward, weaver, this time, brings the odd yarns forward where the heddle returns its original position (Figure 3.15). This procedure is repeated after each row of knots had been woven.

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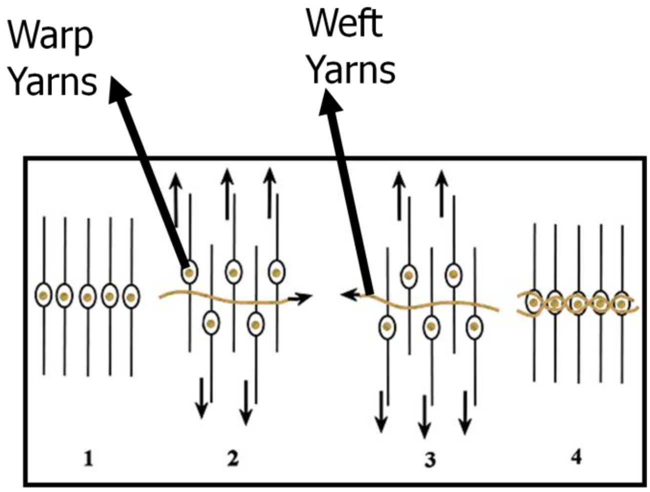

Figure 3.15 Schematic Representation of Wefting Process

In wefting process, main design objective is to actuate odd and even yarns respectively in the desired order. Moreover, this seperating process must create a space for the shutlle motion through the warps.

For this purpose, we design a cam system, for actuating each warp by using rotary motion. Basically this system is composed of a row of cams,one cam for each warp, placed on a shaft and a motor for rotary actuation. The design considerations of this system mainly based on the design of the cams where the requirements of appropriate displacement of warps with a suitable pressure angle and the rigidity of the cams should be satisfied.

The cam profiles are constructed by graphical synthesis method based on the process requirements mentioned above. For a sley motion, space between odd and even yarns after seperation should be at least 60mm. Moreover, as there is only one cam for each warp, thickness of the cams should not exceed 1mm. Thus, pressure angle should be appropriate for avoiding buckling of the cams.

For the graphical synthesis of the cams it would be useful to construct the displacement diagram of the warps. As the velocity of the cams should not exceed 5 rpm and it is important to tense the warps firmly for avoiding rupture, simple harmonic motion model is selected for the design of the cams. Simple harmonic motion is useful to modelize the uniformly changing velocity of the follower. Displacement diagram for the warps is given in Figure 3.16.

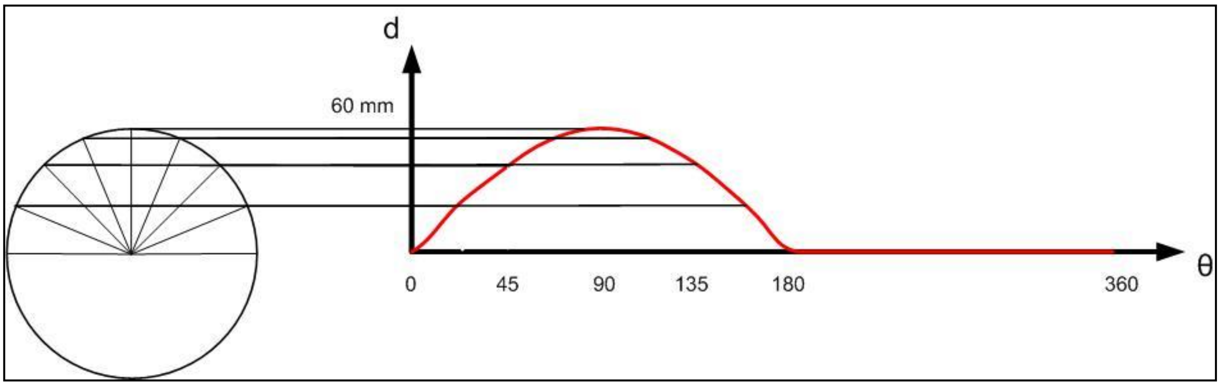

Figure 3.16 Displacement Diagram for warps

Here, θ represents the rotation of the cam where d represents the displacement of the warp from its initial position. According to the diagram, warps are displaced 60mm away when the cam rotates 90^0 and returns to its original position at 180^0. Based on this diagram, graphical synthesis of cam with an appropriate pressure angle is given in Figure 3.17.

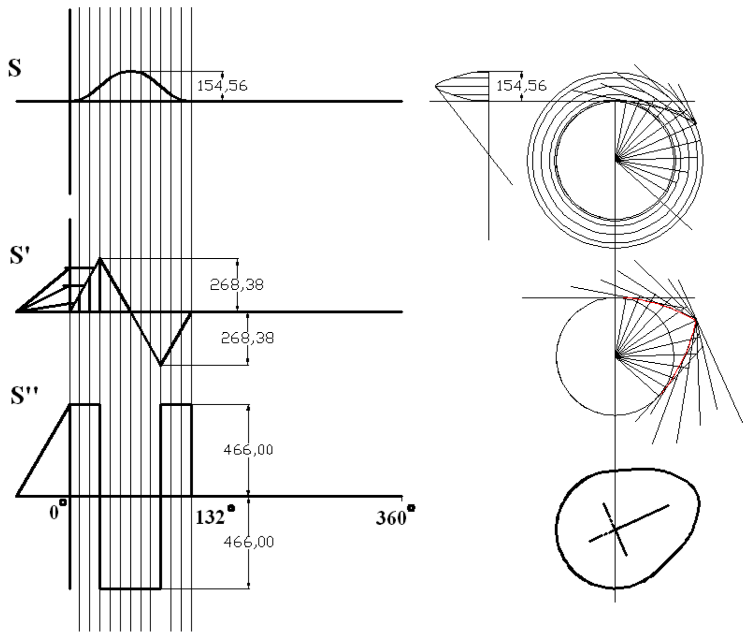

Figure 3.17 Graphical synthesis of cams

For shuttle movement, it is required to place guideway at the tip of the designed cams. Cam design with guideway is given in Figure 3.18.

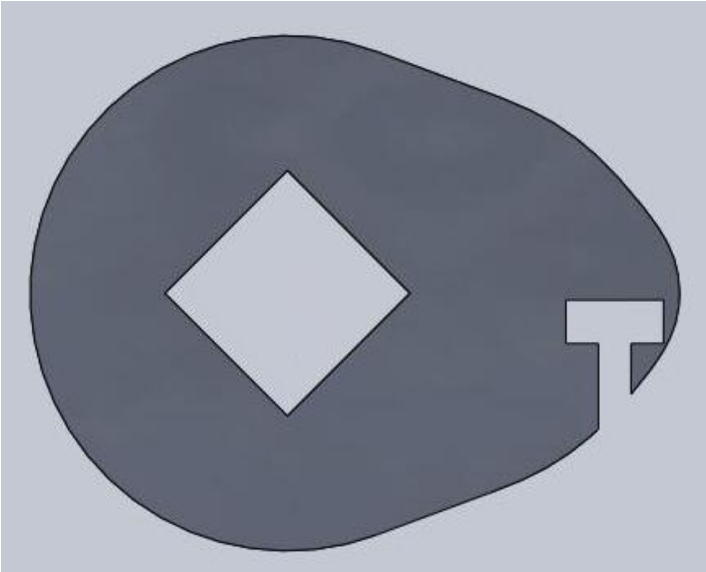

Figure 3.18 Cam design with guideway

Successive cams are placed oppositely, as shown in Figure 3.19, for actuating the odd and even warps individually during one rotation. In this figure, brown cams displaced the odd warps where the pink cams actuate the even yarns.

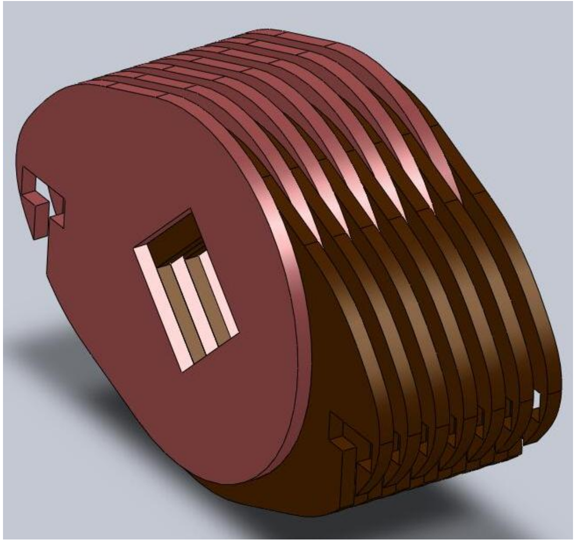

Figure 3.19 Set of designed cams

However, in this system, warps could slip on the cams during rotation. For avoiding this problem, additional ”big” cams placed both sides of “small” cams [Figure 3.20]. These big cams used as guideways for the warps. By this way, uniform spacing problem, mentioned in the previous section, is also solved without using the slots on the cylinder. This point is important for reducing the manufacturing costs.

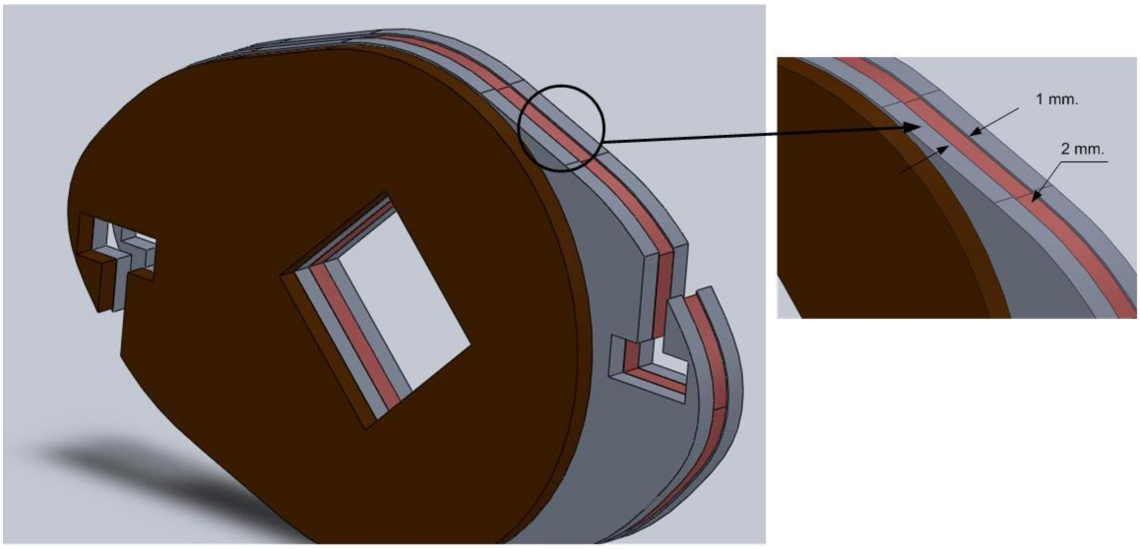

Figure 3.20 Cam system design for avoiding warp slips

Another design problem of the system is the actuation of the cams. Generally, cams are placed on a circular shaft by slot and key. For actuating 600 warps with a spacing of 2mm, requires 1.2 m length circular shaft with slot. However, slotting over a long shaft leads longitudinal deflections. In order to avoid deflection problem, as the rotation speed of the system is too slow (not exceed 0.5 rpm), where effect of moment of inertia can be neglected, the shaft is choosen as prismatic.

Weight of the cams and reaction force of the warps cause bending deflection for the prismatic shaft. As discussed earlier, there are two design constraints in shaft design : eccentricity and maximum deflection. For deep-groove ball bearing acceptable eccentricityis 0.004 rad where the maximum deflection in shaft must not exceed 0.1 mm. Schematic representation of the deflection problem is given in Figure 3.21.

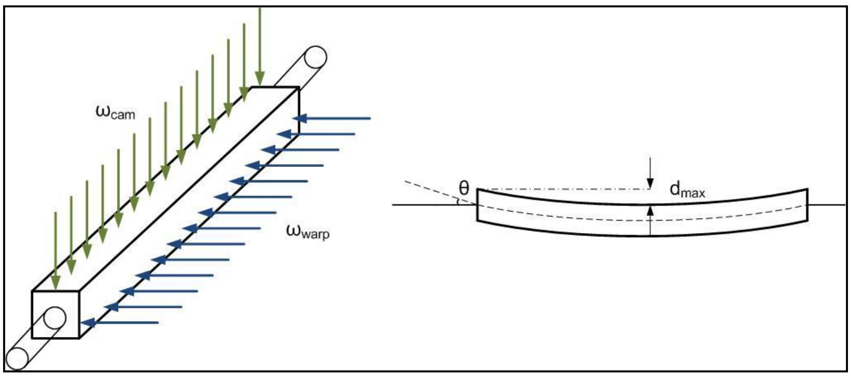

Figure 3.21 Schematic representation of shaft strength design problem

Total mass of the cams is 550 kg which leads 5489 N force on the shaft where each warp applies 10 N force where the resultant force acting on the shaft yields 8200 N. Considering factor of safety as 2, total force distribution on the shaft is 14 kN/m. Taking the design constraints into account by applying Eq. 3.4 and Eq. 3.5 the minimum shaft profile dimensions are given in Table 3.2 for different factor of safety constants.

Table 3.2 Minimum square shaft profile dimensions

Factor of Safety	**B_{ec}(mm)**	**B_{def}(mm)**
1	58.01	52.44
1.5	64.22	58.03
2	69.01	62.36
3	76.37	69.01

Values, given in Table 3.2, are the minimum dimensions for the eccentricity (B_{ec}) and maximum deflection (B_{def}) constraints. This carpet loom is designed not only for the weaving mechanism discussed in this thesis but also for the future designs. Thus, the factor of safety is taken above 3 where dimension of square profile shaft is choosen as 80 mm. The design of the cam system and the shaft is given in Figure 3.22.

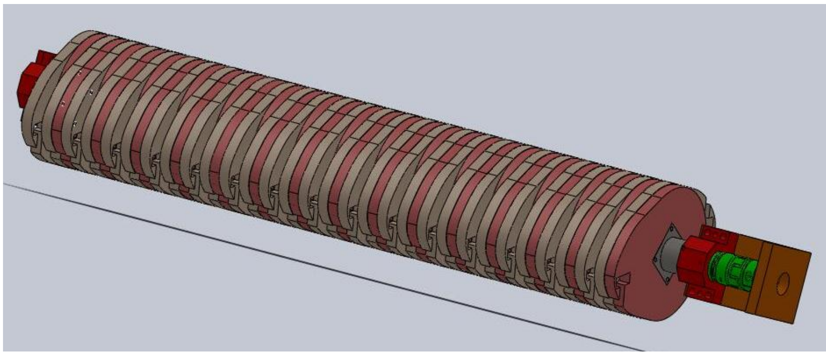

Figure 3.22 Design of cam system placed on the shaft

3.3 Design of Hammering Mechanism

After each row of knots and weft threads are woven, for the sake of quality, both of them must be squeezed. In traditional carpet looms, weaver hits the woven part with a tool called “tarak” [Figure 3.23].

Figure 3.23 Traditional carpet hammering tool (tarak)

However, this process causes local deflections on the carpet when detached from the loom due to non-homogeneous hammering. In order to avoid non-homogenity, hammering process should be made on the row of weaving simultaneously for each knot. In addition, the mechanism or system designed for this process should be simple and easy to manufacture with low cost.

Considering all of these requirements, the design of tarak is attached on the ”big” cams, mentioned in the previous section, as given in Figure 3.24.

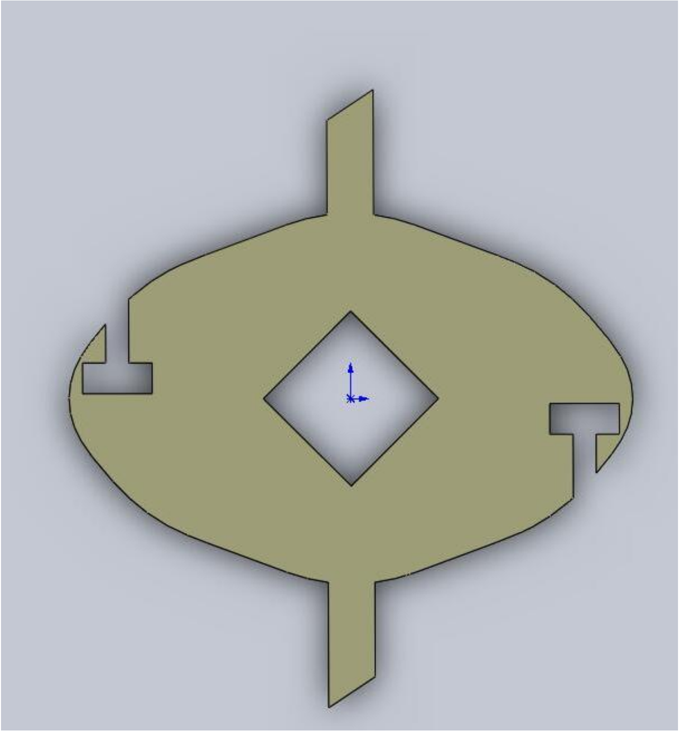

Figure 3.24 Hammering system attached on the designed cams

As a result, by using cam system we have solved three design problems : spacing between the warps, wefting mechanism and hammering mechanism.

Basically, this cam system works in four steps:

1. In the first step, system starts to rotate from its original position. After 90^{o} rotation, "small" cams push the even warps forward where odd warps stay behind. Shuttle passes through the crossed warps by leaving weft yarns behind.
2. For the second step, cam system rotates 90^{o} where the leaves of hammering system are placed between warp yarns. Vertical linear motion module, pulls down the whole system, by squeezing both knots and weft thread on to woven part.
3. This time, as the cam system rotates 90^{o} "small" cams push the odd warps before the shuttle movement.
4. Cycle completed when the second layer of weft thread is squeezed on the woven part.

Design of a fully automated carpet loom is given in Figure 3.25.

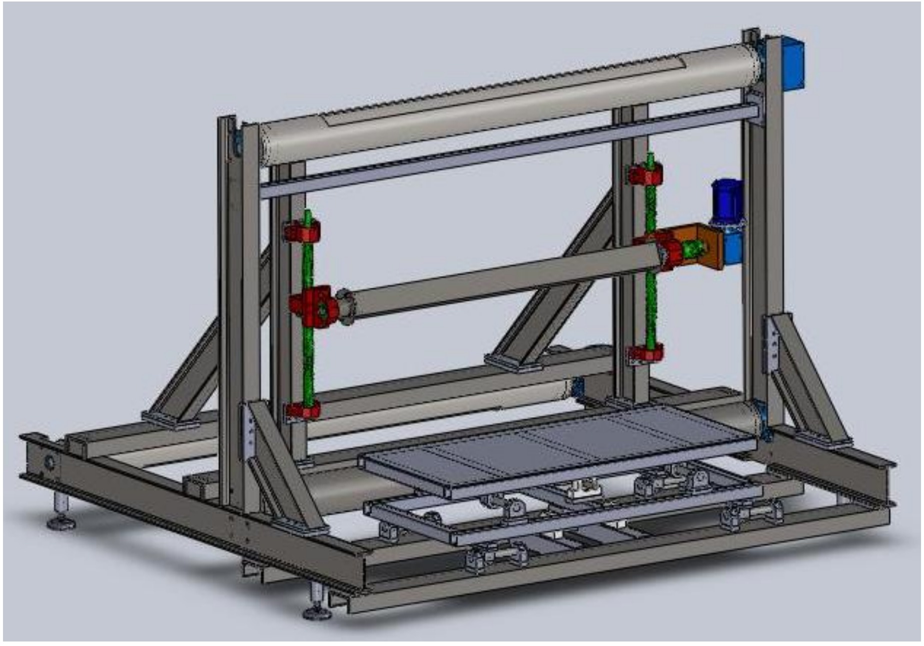

Figure 3.25 Fully Automated Carpet Loom

CHAPTER 4

CONCLUSION

During this study, the main aim is to design micromechanisms and fully automated carpet loom in order to imitate the process of handmade carpet manufacturing. In the light of this, planar two degree of freedom serial manipulator is synthesized with respect to path generation synthesis as a weaver mechanism for the given four precision points on the prescribed path. Linearization method is also given to solve the resulting nonlinear synthesis equations. To reduce the number of motors in designed weaver mechanism, alternative cam-actuated mechanism is proposed. After the analysis of each stages of knotting operation, cam profiles are constructed in the optimized form.

Concluding the studies on the weaver micromechanisms, a new fully automated carpet loom is proposed for real-life manufacturing purposes. After the strength and cost calculations, simulations are performed and the final design is manufactured with respect to given constraints.

In order to extend the study further, as futureworks, control system and software could be designed for industrial applications and quality of the carpet can be enhanced by increasing the resolution of the knots per centimeter square. In addition, for wefting process, a mobile robot carrying the weft yarns through the piles could be designed.

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