Mathematical and Physical Properties of Rope Made for Decorative Purposes

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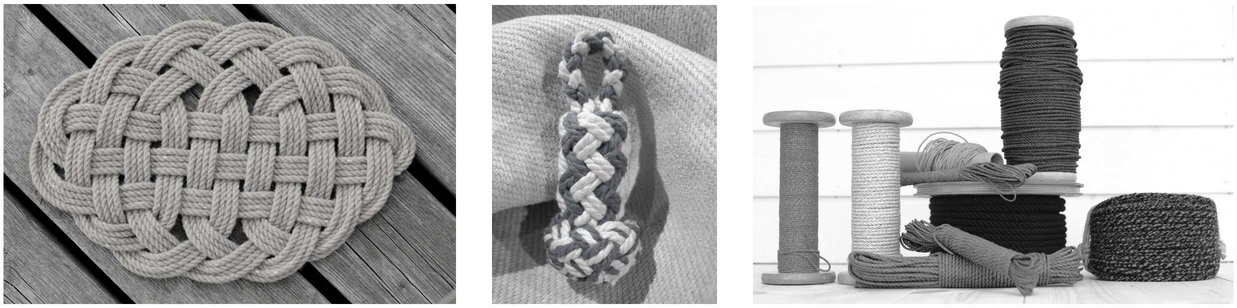
Abstract

In this workshop paper we give a brief introduction to the historical aspects of rope making, different types of materials as well as techniques of construction. We look at mathematical and physical properties of rope and how to adapt these properties when making rope using some basic techniques. During the workshop we present two different techniques of making rope, vertical and horizontal, where both tools are hand operated. The tool we use for making rope vertically is known as a *"Känsespel"* [ɕænsəspe:l]. For the horizontal rope making we compare two machines and describe the advantage of having a gear ratio. We also show the impact of the mathematical and physical properties in the laid rope. We then let the participants create their own piece of rope and elaborate with the mentioned properties of the rope.

Introduction

The use of rope and knots has been a crucial necessity for mankind since time immemorial, and the sector of applications have been wide. Some examples of ancient use (and in some cases still used today) of rope and knots are, hunting, roofing, [22], horse riding, bridge and boat building, sailing, weaving and cloth production [28], fishing nets [13], carrier nets, Basketry, sandals [25], hair nets [15], sling braiding [6], surgery [19] (Ohrvall translates the work of Oreibasios, written in the 4th century AD, an encyclopedia of medical and surgery, where knots are mentioned for assistance) and number systems [2] (The Peruvian Incas used knots to symbolize numbers, called Quipus, this was achieved by systems of cords with tied knots). According to archaeological evidence, the materials used to create rope have seemingly been dependent on the materials at hand. Even though cordage is organic and suffers from decay, some archaeological findings have been made. For instance, in 1989-1991 an excavation of a waterlogged sediment in Gesher Benot Y'akov (Israel) unveiled fragments of twisted fibres, around 19.000 years old [17]. Another example is in Guitarrero cave, Peru, where fifty-five pieces of cordage were found, originating to around 9.000-6.000 years BC [1]. Further cordage findings have been made in San Miguel, California, 9.900 years old [7]. In Pendejo cave [10], cordage were found believed to be of pre-Clovis origin (pre 11.500 BC.). The techniques of producing rope is however a more uncertain topic, the evidence is quite sparse. The earliest contemporary documentation of rope making techniques are those carved on ancient Egyptian tombs, illustrating the laying of rope, see for instance [24].

In this workshop paper, we give a brief introduction to the historical aspects of rope making, different types of materials as well as the techniques of construction. We look at mathematical and physical properties of rope and how to adapt these properties when making rope using some common techniques. We look specifically at mathematical and physical properties that fulfill the requirements put on rope made for decorative purposes. During the workshop we present two techniques with different approaches of making rope and let the participants create their own pieces of rope. To create a personal expression and to increase the aesthetic aspects, such as colour aspects an yarn quality, it is of utmost importance that knots artist is not limited by the existing selection of rope. In Figure 1 we present fancywork created with non commercially available rope.



(a) (b) (c)

Figure 1 : *Examples of fancywork and rope created with non-commercially available rope and yarn respectively: (a) Half-hitch mat made with wool rope, (b) multi-strand knot made with cotton rope, photographed by C. Åström and (c) examples of rope.*

Materials

We look at a few different types of materials that have been used for making rope, and in some cases, still are in use as of today. To indulge and attend to the Scandinavian traditions and as well to promote the cultural heritage, we only look at natural materials throughout. To some extent, natural materials are still in use in present day. In fact, it is the preferred material when making fancywork in the northern parts of Europe. See Figure 2 (a) for an example of hemp yarn and Figure 2 (b) for modern produced Coir rope.

(a) (b)

Figure 2 : *Examples of different rope materials at the Naval Rope-walk on the Island of Lindholmen in Karlskrona, Sweden: (a) yarn made of hemp and (b) modern produced (pre-1960) Coir rope. Photographed by A. Åström 2015-10-10 and 2010-10-09 with permission from the museum.*

From the archaeological encountered pieces of rope, it is evident that the material used to create rope are often from local contexts. Thus, from an archaeological point of view it can be seen that man adapts to what the surrounding nature has to offer depending on the availability of material. For example, Myking et. al. [16] argues that lime bast (from *Tilia*) have been used for rope making in Europe since Mesolithic times (9000 - 3000 BC.) up to present day. Other examples of plants that have been used for making rope: Manilla (*Musa textilis*), Sisal (*Agave sisalana*), Hemp (*Cannabis sativa*), Flax (*Linum usitatissimum*), Jute (*Corchorus*), Cotton (*Gossypium hirsutum, Gossypium barbadense, Gossypium arboreum, Gossypium herbaceum*), Cocos (*Cocos nucifera*), Pine trees (*Pinus*), Birch (*Betula*). Examples of materials from the animal kingdom that have been used for making rope: Walrus hide (*Odobenus rosmarus*), Wool from Sheep (*Ovis aries*) or Musk-ox (*Ovibos moschatus*), camel (*Camelus dromedarius, Camelus bactrianus*). Materials for making rope are for example handled in Wahlbeck [27].

Methods of Construction

Historically, we have two main categories of construction methods for rope, laid rope and braided rope. The former, can be further divided into two different methods, vertical (only used for shorter rope making, $\sim 0.5 - 2$ meter) and horizontal, the result however, is equivalent. The later method can be further divided into, braided and plaited rope. For references of ancient methods see for instance, Mckennan [14] who writes about rope making in Egypt 700 BC, where the ropes have been laid, see also Veldmeijer [26]. Further, Nilsson [18] writes about rope making as a technology in the Swedish country side after the industrialisation, but techniques that very well can be an ancient methods of rope making. For a thorough and systematic description about the properties of cordage, see Mckennan [14], see also Wahlbeck [27] for an overview of rope and rope making. Figure 3 shows two examples of tools that are used for making rope. The terminology of rope and its different parts often differs in the literature, depending on field of applications or context, etc. Some terms are however more used than others, for instance those used in Himmelfarb [9] and Osborne [20], which is the terminology we use throughout this paper. There is also a terminology in use for the analysis of cordage and the different stages of the production process, see Dixon [8]. These stages are referred to as: *Stage I - Stage IV*. Stage IV is only relevant for cable laid rope production, which is why we only refer to Stage I - III throughout. Note however, that historically cables have been produced to be rather thick, with some exceptions. But for the knot artist who produces his own rope, cable laid rope might extend the decorative effects further. For instance different colours, texture, etc., the downside is however reduced strength. The first three stages of the production process of a laid rope can be described as the following:

(a) (b)

Figure 3: *Examples of Tools for making rope: (a) portable tools for vertical production, known as a* "Känsespel" *in Swedish and (b) tool for horizontal production at the Naval Rope-walk on the Island of Lindholmen in Karlskrona, Sweden, photographed by A. Åström 2015-10-10 with permission from the museum.*

(I) A number of fibres (the smallest component of a rope) are twisted together to create a yarn.

(II) A fixed number of yarns twisted together, with opposite rotational direction as a single yarn, forms a strand.

(III) A fixed number of strands twisted together, with opposite rotational direction as a single strand, forms a rope.

Figure 4 shows an illustration of the different parts of a rope. Commonly, a rope consists of three strands, however other combinations, such as two, four and six strands occur but are not as common. Note that the above process only applies to laid rope and not to braided ropes. The strands of a braided rope have a more complex relation to one-another than the strands of a laid rope. In a braided rope, every second strand is twisted in one direction and the next one in the opposite direction. Each strand is then braided with the opposite direction as itself in the braiding procedure. A braided rope always

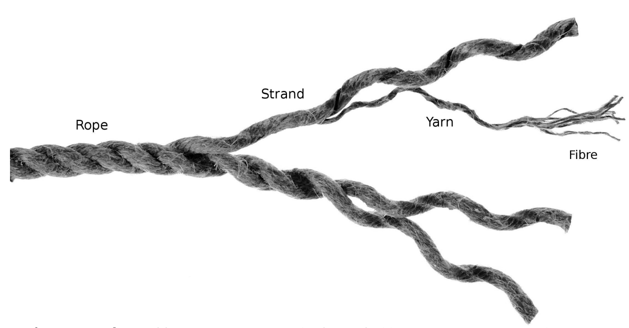
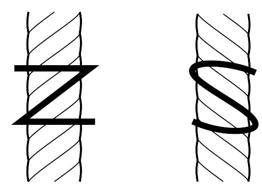


Figure 4: *Illustration of the different parts of a rope.*

has the same amount of strands in both twist directions. Odd number of strands in a braided constructions does not give a round rope but rather a *band* shape. A laid rope you can loosen the strands by twisting the rope in opposite rotation direction of the strands (refer to Figure 4). A useful property for splicing of ropes. Note also that a laid rope can consist of two strands, while a braided rope need four strands as a minimum. Another important matter in the construction of rope is to know when a rope machine with gear ratio is needed or not. In general, the principle is to have a high gear ratio for thin ropes and a low, or no gear ratio at all, for thick ropes. Without a high gear ratio the amount of time needed to reach the required level of twist in a thin rope could be extensive. A thick rope requires more force to reach the necessary level of twist and does not need as many turns per unit of length which is why a low gear ratio is preferred.

Rope Properties

Two important properties for rope concern the twisting: direction of twist and the degree of twist. A rope can be twisted in two directions, as discussed in the previous section, this is described as *Z*- or *S*-twisted, according to ISO-standard [11], see Figure 5. Historically these have been described as being right-handed and left-handed laid rope respectively. This is clearly a rather confusing terminology, since it does not describe what it actually means. It is sometimes referring to how the rope has been laid out and sometimes referring to the appearance of the rope, but not the orientation. This is why it is an unfortunate terminology which should be avoided. Using the terms *Z*- and *S*-twisted we can describe how a rope is made, for example *SZS* indicates *S*-twisted fibres, *Z*-twisted yarns and *S*-twisted strands. This would normally be referred to as an S-twisted rope. Another method used for machine-laid rope (post-medieval) is S^2Z, thus, both fibres and yarn are twisted in the same rotational direction, see Sanders [23]. Clearly, a strand will not stay twisted since the rotational direction is the same for both fibres and yarns. In Wendrich [29] the term *I* is also used, which indicates that there is no twisting of the fibres (or yarns).



(a) (b)

Figure 5: *Illustration of the direction of twist in a helical structure: (a) Z-twisted and (b) S-twisted.*

The degree of twist in a helical structure can be measured by the helix angle. The angle is measured relative to the direction of the rope, we denote it by γ, see Figure 6 (a). In Figure 6 (b) an actual rope is shown with a clearly defined helix angle. Another possible way of measuring the degree of twist is by the number of turns per unit of length. From an archaeological point of view this has the downside that the diameter of more primitive yarns may be irregular and thus the result could be unreliable, see Osborne [20]. Throughout we use the helix angle to measure the degree of twist. In Bohr [4] it is showed that the maximum number of rotations for a helical structure (e.g. twisted rope) is a geometrical property rather than a material property. This gives at hand that ropes made of completely different materials can show identical characteristics.

(a) (b)

Figure 6: *Visulization of the helix angle in Z-twisted helix structure: (a) Illustration showing how the helix angle, γ, is measured and (b) a laid hemp rope with $\gamma = 37^\circ$ consisting of three strands.*

Further on, there is a direct correlation between the degree of twist and how hard or soft the structure is. We measure the angle in regards to the direction of the helical structure, thus, the interval is $0° < \gamma < 90°$. However, below $15°$ and above $55°$ is not very useful in practice for most applications, most certainly not for decorative purposes. In, for instance, Barker [3] and Osborne [20], different angle intervals are stated, for example $\gamma = 10°$ is described as *soft*, $\gamma = 20°$ described as *medium* and so on. In fact, for decorative purposes, the rope is preferably between $25° < \gamma < 30°$. A rope which is twisted too hard, will be difficult for the knot artist to work with and form the rope as intended. A rope that is twisted too loose will on the one hand be easy to lay out and form according to ones needs, but on the other hand the finished knot product will not stay in shape, it will tend to be somewhat loose and floppy.

Tensile strength is an obvious property of a rope for several applications such as securing a boat or rock climbing. For a rope to be strong the fibres of the rope need to be longer to make the yarn strong (applicable for both natural and synthetic material). The tensile strength is perhaps not such an obvious property of rope made for decorative use, but there is an indirect correlation. If the fibres are instead short, the yarn and subsequently the rope will be a bit *fluffy*. This could however, for various reasons, be desired. The thickness of the yarn is dependent of the fibre length as well. An example of a material with short fibres is cotton, which gives that cotton yarn has a limited thickness compared to for instance hemp and manila.

Another important physical property when working with rope is the humidity, which will affect how soft or hard the rope will be, thus how pliable it will be. The humidity is significant for both the process of manufacturing the rope as well as the activity of using the rope, in our case, using the rope for decorative purposes. This makes it important to know what the rope will be used for already when laying the rope. If the rope is layed in an environment with a high humidity and later on the humidity is lowered, the rope will dry up and become looser (the helix angle will decrease). If the rope instead is layed in an environment with a low humidity and the humidity later on increases, it will become harder (the helix angle will increase). Thus, using rope to create fancywork, different humidity is desired which depends on the field of application. Note also that different materials are affected to different extents by the humidity.

An important activity when preparing for rope making is to calculate the amount of materials needed, thus the total length of yarn. This is a quite complicated procedure since several parameters affects the result. The function for the length of a laid rope L_r have the following arguments: $L_r = f_r(n_s, d_s, \gamma_R, L_s)$, where n_s i the number of strands, d_s is the diameter of a strand, γ_r is the helix angle of the rope and L_s is the length of the strands. The strand diameter and strand length are in turn functions with following arguments: $d_s = f_d(n_y, d_y, \gamma_s, \Phi, \tau)$ and $L_s = f_s(n_y, d_y, \gamma_s, \Phi, \tau, L_y)$ respectively. Where n_y is the number of yarns, d_y is the diameter of a yarn, γ_s is the helix angle of a strand, Φ is the humidity, τ is the tension in the strands and yarns during the rope making process and L_y is the length of the yarn. Various approximations for calculation of rope length given the strand or yarn length can be used, with more or less accuracy. In [9] the following approximation is given: $L_r = L_s cos(\gamma_s)$, thus using only the strand length and helix angle as parameters. Another alternative is to calculate the arc length of a circular helix curve.

Workshop

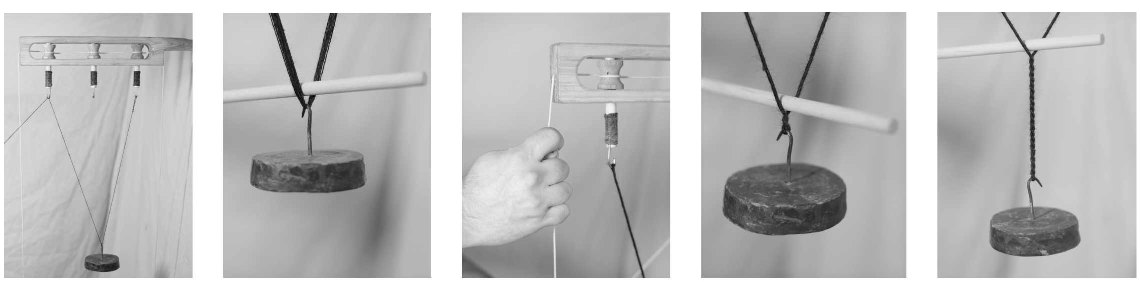
We start with a short presentation of the purpose of the workshop and the main focus areas. For obvious reasons we will omit the demonstration of the impact of humidity and rather work with the conditions at hand. We will then perform a short demonstration of two different techniques of laying rope, a vertical method and an horizontal method. The former, will approximately produce ropes with a length of $\sim 0.5 - 2$ meter. The later method allows us to create longer ropes. Due to time limitations we focus on the second and third stages in the rope making process, twisting yarns into strands and then twisting the strands into a rope.

Arguably, these are the most important steps in the process, at least for the rope applications specific for this workshop. Finally, we start with the main activity of the workshop, where we let the participants create their own pieces of rope. For the vertical tools at hand (approx. 7 sets), we recommend two participants to operate each of the tools. For the horisontal tools (approx. 3 sets) we recommend three participants to operate each of the tools.

Instructions for use of the vertical tool

We create a piece of rope consisting of two strands. For the actual tools we use for the laying of vertical rope, there is an important condition that needs extra attention, the tension of the rope. The weight that pulls down the rope is in direct correlation to the diameter of the rope. Thus, too much weight and the rope will snap and too little weight and the rope will tend to *hockle*. Note that the pulley diameter of the känsespel is dimensioning the relation between the travel distance of th drive line and the rotation speed of the hooks.

1. Attach the känsespel to a wall, table or something equivalent with sufficient height and place the weight directly underneath the känsespel.
2. Attach the loose end of the yarn to one of the outermost hooks on the känsespel and pull the yarn towards the weight through the hook on the weight and then back towards the känsespel. This time the yarn shall pass through the second outermost hook. (Note that the middle hook is not used for two stranded ropes.) Repeat the procedure until the desired number of yarns have been reached and both hooks have the same number of yarns attached to them. See Figure 7 (a).
3. Place a pencil, or equivalent, between the strands just above the hook on the weight. See Figure 7 (b).
4. Start pulling the string attached to the blocks on the känsespel, see Figure 7 (c), while holding the pencil in an unchanged position in relation to the weight. The pencil is kept in position until the required twist has been reached, see Figure 7 (d). Note that this step of the process is equivalent with, what is referred to as *Stage II* above.
5. Move the pencil upwards at the same time as pulling the string in a steady pace until reaching the känsespel, see Figure 7 (e). Note that this step of the process is equivalent with, what is referred to as *Stage III* above.
6. Let the rope rotate until it stops, thus equilibrium has been reached.



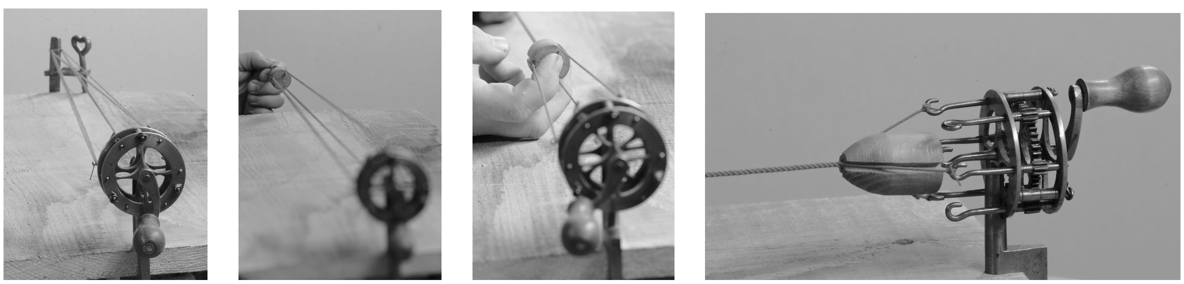
(a) (b) (c) (d) (e)

Figure 7 : *Illustration of the instruction steps for ropemaking with a känsespel: (a) yarn is attached to the känsespel and the weight, (b) a pencil is used to keep the weight from turning, (c) the string attached to the blocks on the känsespel is pulled downwards, (d) the pencil is kept in position in relation to the weight and (e) the pencil is pushed upwards until reaching the känsespel.*

Instructions for use of the horizontal tool

We create a piece of rope consisting of three strands, the most important steps in the process are described below. The machine presented below have a gear ratio of $\sim 1:6$ which reduces the revolutions needed for the crank handle. (Note that there is not a one-to-one mapping between the different stages described above and the following steps.)

1. Make sure that the *swivel* is fixed such that the strands are not able to twist. The first part of the process consists of strapping down the loose ends of the yarn. Start with one strand at a time, attach one loose end of the yarn at the hook on the *traveler* and the other one at one of the hooks on the rope machine. Repeat until the desired number of yarns have been reached for the given strand and make sure that all yarns have the same length. Repeat for the remaining strands and make sure that all strands have the same length and same number of yarns. See Figure 8 (a).
2. Start turning the handle of the rope machine with a constant velocity in the preferred direction and note that the traveler will move towards the rope machine. Continue until the desired helix angle has been reached for the strands. Notice the direction of twist in the strands. Note that this step of the process is equivalent with, what is referred to as *Stage II* above. See Figure 8 (b).
3. Place the *top* so that each strand can slide in one of the three slots, then release the swivel so that it can twist in any direction. Start turning the handle of the rope machine again, in the same direction as for the twisting of strands in the previous step. At the same time move the top forward, towards the rope machine, with a constant velocity. See Figure 8 (c) - (d). The velocity in which the top is moved forward is correlating with the degree of twist in the rope. Again, notice the direction of twist in the rope. The purpose of the turning of the rope machine's handle in this step, is rather to make the strands stay twisted rather than twisting of the rope. Note also that this step correlates to *Stage II - III* above.



(a) (b) (c) (d)

Figure 8 : *Illustration of the instruction steps for ropemaking with a horizontal tool: (a) yarn is attached to the hook of the traveler and the hooks of the rope machine, (b) the handle of the rope machine is turned in order to twist the strands, (c) the top is pushed in a constant velocity towards the rope machine and (d) the top have reached the rope machine.*

Note All figures and images are either made by or photographed by A. Åström if not stated otherwise.

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