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A Motorized Turntable System

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1 Overview

This report presents a design for a generic turntable system capable of use in a number of different theatrical situations. The turntable is twenty feet in diameter, and designed to support a load of at least ten thousand pounds. Some unusual features of the design include a purely laminated-plywood platform design. By constructing the platform from a number of identically-shaped sections, this speeds the process of construction. In addition, since it uses modular sections, it can be easily disassembled, stored, and reassembled for later uses. The turntable is driven using a 2 HP motor and a roller chain drive system. The use of a roller chain drive system instead of a friction or cable drive system makes installing and adjusting the drive loop simpler.

2 Requirements Analysis

We begin by examining the requirements for this system. This turntable not being designed for an actual production, we do not have specific figures in mind. We make some general assumptions about the types of loads the turntable will be subjected to, and its uses. This is a reasonable design approach, since a turntable of the size we are considering is a major scenic mechanism. One would like to be able to reuse it for multiple productions — the turntable itself can only be reused if space permits it to be stored, but in any case we would like the design to be reusable without too much modification. Again with reusability in mind, we note that a mechanism of this scale may be somewhat expensive, but this is to be expected; if the design is reusable, then the expense is not such a great concern. Of course, we would like to keep the budget as low as is reasonably possible, as always.

The intended use of this turntable is to rotate a full set — or at least major portions of one. Hence, it will be a circular turntable twenty feet in diameter (approximately 63 feet in circumference, and approximately 315 square feet in area). It is to support a load of ten thousand pounds. We assume the load will be evenly distributed over the area of the turntable. This assumption is clearly not entirely realistic, but it supports our goal of generality, and many designs will approximate a uniform loading. Nevertheless, there are clearly cases where this assumption becomes problematic: if all the load is at the edges of the platform (a set of walls around the edge, perhaps), the turntable's capacity will have to be de-rated.

We would also like to consider the speed and torque requirements. Rather arbitrarily, we would like the turntable to be able to complete one rotation per minute — this corresponds to an average edge velocity of about 63 feet per minute, or about 0.7 mph. We also prepare for the worst cases in dynamic torque applied by the load: we suppose the director, prompted by Murphy's law, will call for twenty actors to walk briskly around the edge. To calculate this, we assume that the contact force applied by the actor's feet will be approximately at a 45° angle, i.e. the horizontal and vertical components are equal[1], and that the actors average 150 pounds. Then the torque applied is

$$\begin{aligned} \tau &= 20rmg && (1) \\ &= 20\,(10')\,(150 \text{ lbs}) && (2) \\ &= 30,000 \text{ ft lbs} && (3) \\ &\approx 40,674 \text{ Joules} && (4) \end{aligned}$$

3 Platform construction

The body of the turntable is essentially a platform that supports the actors and is itself supported by a set of casters. A traditional turntable design will use a typical platform design: a frame of sawn lumber with plywood panels attached. Since the platform is so large, it must be divided into sections — typically either $4' \times 8'$ stock platforms plus special rounded edge platforms, or wedge-shaped platforms. These platforms must be aligned and secured together. The process of alignment is non-trivial, since various oddly-shaped platforms will be required, and these will need to be carefully constructed.

Instead, we use a variation on designs proposed by Sullivan [1] and Holden [2]. This design calls for the turntable to be constructed from laminated plywood sections. This neatly avoids the problem of constructing frames by eliminating them entirely. Moreover, it uses wedge-shaped sections that are identical, which simplifies construction greatly. This is an advantage over designs that use stock $4' \times 8'$ platforms, because those require multiple different types of smaller rounded platforms at the edges that must be carefully designed and constructed to fit together.

[1] This assumption is really not justifiable for any precise applications; it serves only as a quick approximation.

The design divides the 20' turntable into a 5' diameter disc-shaped inner section and a ring-shaped[2] outer section that completes the 20' diameter of the turntable. The outer section is divided into twenty wedge-shaped segments. This is shown in Figure 1.

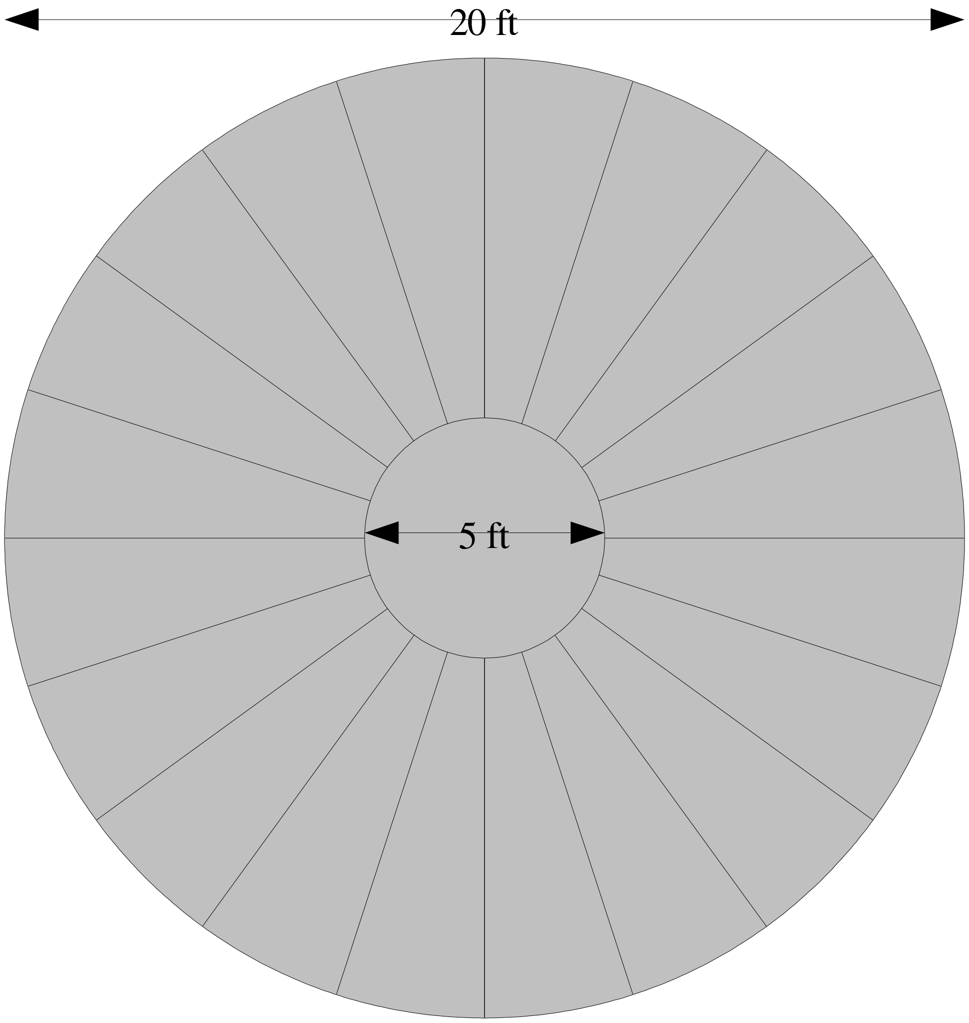

Figure 1: Overview of platform design

The outer sections are constructed by cutting sixty identical wedge-shaped sections of $3/4''$ plywood. Initially, the wedges should simply be cut with the straight edges shown as solid lines in Figure 2; the dashed-line curved edges will be cut later. The size of the sections was chosen so that they can be easily cut from a $4' \times 8'$ sheet of plywood; Figure 2 shows how one wedge can be cut from the sheet, and the remaining

[2]Or an annulus, if you prefer such terms

plywood on the sheet can be used to cut a second identical wedge.

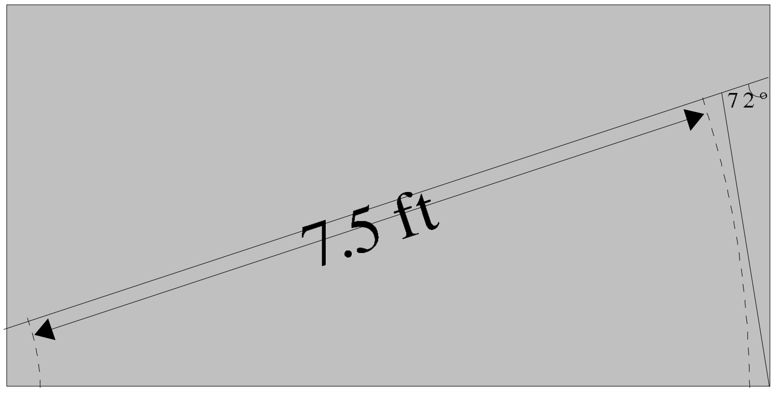

Figure 2: Cutting a wedge from a $4' \times 8'$ sheet of plywood

Three wedges will be laminated together to form each section, as in Figure 3. The three individual pieces are offset by 3 inches away from the inner edge and away from the factory edge of the plywood. It is important to note that this is a translational, not rotational offset, i.e. the next piece is shifted from the piece it attaches to, with the edges still parallel. This ensures that there is a constant 3-inch offset between each piece; if it were offset rotationally, the offset would decrease toward the center, which would make for a less secure joint between adjacent segments.

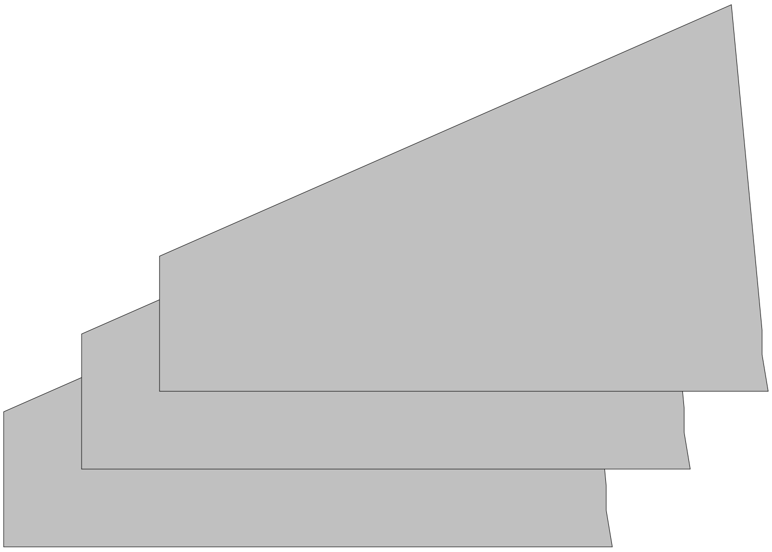

Figure 3: Arrangement of wedge-pieces for lamination (not to scale)

The following method is probably the easiest way to construct the outer section:

first, lay out a full ring of 20 wedge pieces, using only a single layer. This layer should then be trimmed into a ring (probably using a router) with an outside diameter of $19'6''$ and an inside diameter of $4'3''$. Next, the second layer can be added after a thorough coating with wood glue. It should be trimmed to an outside diameter of $19'9''$ and an inner diameter of $4'6''$. Following the same procedure, the third layer can be added with outer diameter $20'0''$ and inner diameter $4'9''$. This process will probably go more smoothly if the wedge sections are actually cut $^1/_8''$ or so smaller than their nominal dimension, to account for imprecisions and errors in alignment [2].

The center section is a $5'$-diameter disk, also constructed from laminated plywood. Since the disk cannot be cut from a single sheet of plywood, it needs to be constructed using six semi-circles. The highest disk should have a $5'$ diameter, and the two below it should have diameters of $4'9''$ and $4'6''$ respectively. The semi-circles are to be arranged such that the joins at each layer are perpendicular to the one below. A plan is shown in Figure 4.

Once constructed, the center disk section and the outer wedge sections can then be joined together during put-in. Since the plywood-laminated sections are constructed with offsets, it is simply necessary to arrange the pieces with the overhang of the center disk section matching the underhang of the outer wedge sections. Similarly, the layers of the outer wedges should mesh together. This is shown in the section view in Figure 5. The joins can be made using screws or bolts through each overlapped area.

The layered structure of the outer ring has the nice property that sweeps can be added (as shown in Figure 5 to the bottom layer, turning the outer edge of the middle layer into a groove. This is ideal for the drive chain, since the upper layer and bottom sweeps ensure that there is no danger of the tensioned chain slipping out of its groove.

The total wood requirement is 30 $4' \times 8'$ sheets of $^3/_4''$ plywood, plus another 6 for the center section, and smaller pieces to complete the sweeps. This is all that is required to construct the platform; no sawn lumber is required.

Optionally, the platform may be surfaced with whatever decking is appropriate for the specific use (perhaps a layer of masonite, etc.).

After the show, the sections may again be separated. The turntable breaks down into sections of a reasonable size for storage (provided space is available, of course). It can later be reassembled the same way.

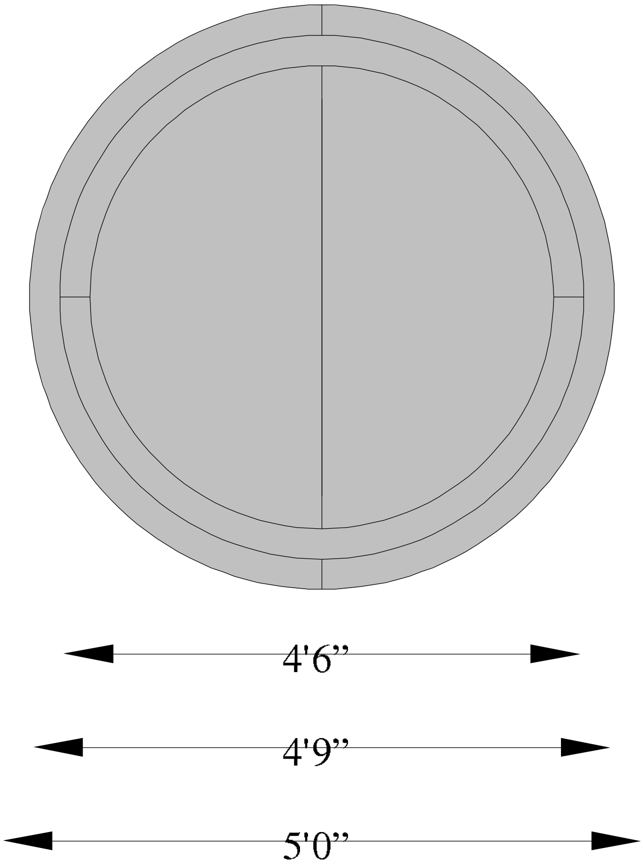

Figure 4: Plan for the center section (bottom view)

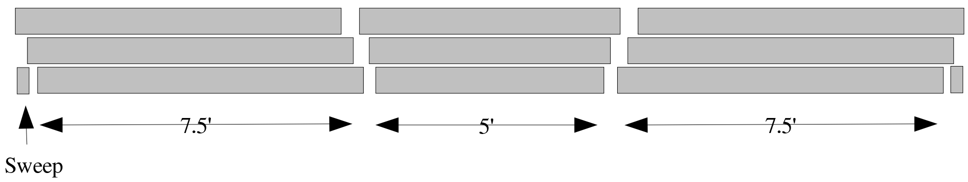

Figure 5: Platform assembly (exploded section view, not to scale)

4 Driving the turntable

We now turn[3] to the problem of making the turntable turn. As usual, we use casters to support the turntable and allow it to rotate. The casters are mounted to the floor rather than the turntable, so that they can be more easily adjusted to account for a non-level floor[4]. Since the bottom surface of the turntable is flat — it is, after all, made of plywood — there should be no problem with mounting the casters on the floor.

To ensure that the turntable moves smoothly, 4″-diameter casters are used. Forty of these casters are arranged in three circles concentric with the center of the turntable: six at a radius of 6′, 14 at a radius of 12′, and 20 at a radius of 18′. This ensures that casters are spaced approximately three feet apart, both radially and circumferentially.

The center pivot is simply constructed from a length of 1 1/2″ Schedule 40 pipe and two flanges. These readily available parts can be assembled into a pivot by attaching a flange to the floor and another to the bottom of the turntable, then connecting them with a heavily-greased 5 1/2″ section of pipe. Holden [2] notes that power cables, if any are required for practicals on the turntable, can be threaded through the pipe (if so, a larger diameter pipe, e.g. 2″ or 2 1/2″ might be more appropriate, but the design is otherwise identical).

A chain drive system is used to operate the turntable. This is similar to a cable-drive system, but uses roller chain instead of aircraft cable. This has several important advantages. Foremost, the chain is easier to work with in a few key ways: it does not need to be spliced, but can simply be connected together using an extension link, which makes it possible to construct the necessary loop without much effort, or to later change the length of the loop. Also, it is no longer necessary to deal with drums or sheaves; the only necessary hardware for the chain are sprockets. Eighty feet of #40 chain is specified. This is enough length to make a full loop around the turntable plus an offset for the motor, which can be located up to 8 feet away from the edge of the turntable. If more distance is required, more chain can be added.

The chain is wrapped around the turntable, then past two idler sprockets to the motor, as in Figure 6. The motor is attached to a 3.196″ sprocket through a 20 : 1

[3]Sorry. I couldn't resist.

[4]Not that we know of any theaters that have non-level floors...

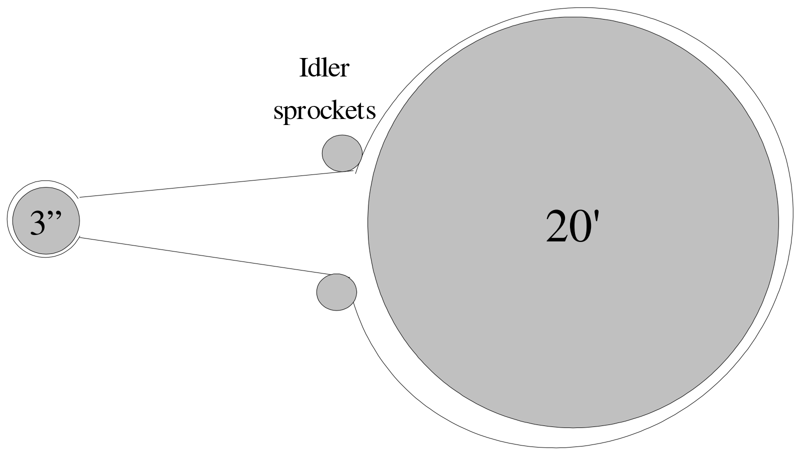

Figure 6: Drive configuration (not to scale)

speed reducer. This provides a speed reduction factor of

$$20\frac{(20\pi)(12)}{3.196\pi} \approx 1502 \tag{5}$$

which can reduce a 1725 RPM motor output to 1.15 RPM, a quite satisfactory rotation speed for our turntable. This gear arrangement results in the following available torque with a 2 HP motor: [5]:

$$\tau = \frac{2 \text{ horsepower}}{1.15^{1}/_{\text{min}}} \tag{6}$$

$$\approx 77,812 \text{ Joules} \tag{7}$$

We consider the moment of inertia of the turntable to be that of a disk whose mass is evenly distributed over its area, and suppose that it supports a mass of 15,000 pounds. This accounts for the specified 10,000 pound load, and provides a conservative overestimation for the weight of the turntable[6]. Using the standard

[5] In performing our calculations here, we implicitly convert from imperial to metric units. Though this adds the confusion of converting between units, it avoids the infinitely more confusing common usage of a *pound* as both a unit of mass and a unit of force ("the gravitational force exerted on an object with a one-pound mass"). Since we deal with both mass and force here, it is far less confusing to use the metric system, where there is no confusion between the unit for mass (the kilogram) and the unit for force (the Newton).

[6] Again, this estimate is not particularly accurate, but we have chosen to err on the conservative side whenever making assumptions, to ensure safety.

relation $I = {}^{1}\!/\!{}_{2}mr^2$, this gives us the following inertial moment:

$$I = \frac{1}{2}15,000 \text{ lbs}(10 \text{ feet})^2 = 750,000 \text{ ft}^2 \text{ lbs} \tag{8}$$
$$= 31,605 \text{ m}^2 \text{ kg} \tag{9}$$

So with this moment of inertia, the turntable will be able to support an angular acceleration

$$\alpha = \frac{\tau}{I} = \frac{77812 \text{ J}}{31605 \text{m}^2 \text{ kg}} \tag{10}$$
$$\approx 2.46 \frac{\text{rotations}}{\text{s}^2} \tag{11}$$

which is more than satisfactory for our requirements. Note also that the available torque, 77,812 Joules, exceeds the torque applied by actors moving around the edge of the stage, which we figured at 40,674 Joules in Equation 4. This means that the turntable's motor will not be overpowered by that adverse loading condition. So our choice of motor is adequate — two horsepower does not sound like much, but between the gearbox and the turntable-sprocket ratio, the speed reduction is massive.

Of course, this power will be useless if it cannot be transmitted to the turntable. Roller chain has a high transmission efficiency in general, but the turntable is not a sprocket. Hence, the chain must be maintained under tension in order for it to grip the turntable and turn it with the necessary torque. We accomplish this using a tensioner design by Hendrickson [3]. The mechanism is shown in Figure 7.

This design mounts the motor, gearbox, and sprocket assembly to an inner frame (not shown explicitly in the diagram), which is mounted with slide rails to an outer frame. The inner and outer frames are connected by two tensioners: a turnbuckle connected to a drawbar spring. The turnbuckle can be tightened to stretch the spring. The spring then pulls on the inner frame, pulling the motor-gearbox-sprocket assembly away from the turntable. This applies tension to the drive chain, allowing it to efficiently transfer torque to the turntable. The rated maximum breaking strength for the chain is 4,290 pounds, which translates to a working load limit of 858 pounds after applying a 5 : 1 safety factor (appropriate since this chain is not being used for overhead lifting or in a safety-critical application). This is sufficiently greater than the tension that will be applied to the system by the spring. A tension of

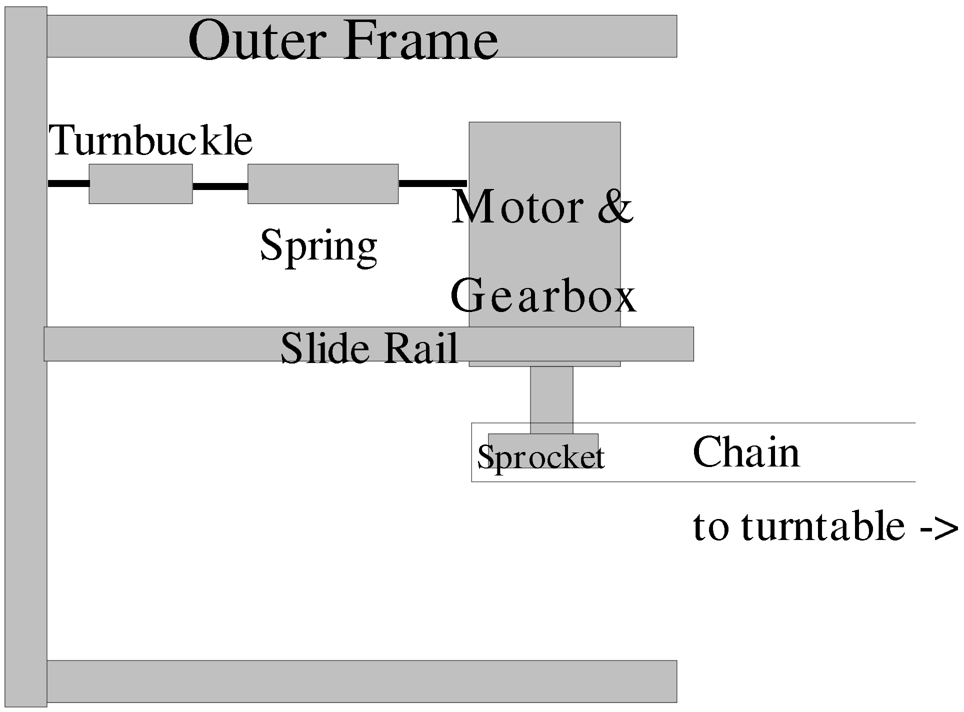

Figure 7: Tensioner mechanism assembly (section view, not to scale)

approximately 100 pounds should be sufficient. Drawbar springs — extension springs that extend to a stop — are used, to prevent the spring from breaking if the turnbuckle is overtightened.

To prevent the turntable from moving when it is not supposed to move, a brake is needed. We choose a 2 HP brakemotor, which both provides enough torque to drive the turntable and the capability to brake it when it is not moving. This brake is capable of holding the turntable in position even when subjected to the worst-case torque loads such as the twenty actors moving around the edge (Equation 4).

Since we do not have a specific application in mind for the turntable, we cannot specify an application-specific control system for it. We simply use a generic switched-motor configuration. The motor requires three-phase AC power (while this is somewhat less convenient to obtain a source of in the theater than single-phase power, it makes selecting a motor much more straightforward), so the controller will need to be able to switch all three phases. This calls for what is essentially a heavy-duty three-pole switch. A motor starter could also be used, which provides some degree of overcurrent protection, but this seems like a bit of unnecessary complexity for this simple application. The switch turns on the motor when desired, and activates the brake otherwise. This process could also be automated somewhat by placing limit microswitches at appropriate locations under the turntable and triggering them with protrusions from the bottom of the turntable (spaced between the rings of casters, of course). These microswitches can be wired to a contactor in series with the motor to start and stop the motor at the appropriate times. Since this depends so heavily on the application, we cannot present a generic example here, as it would not be very meaningful.

The mechanical components required to construct and drive this turntable system are listed in Table 1. The only other requirement is the 36 sheets of $3/4''$ plywood mentioned above for constructing the platform. The design is very simple in this respect.

Item	**Source**	**Price**	**Quantity**	**Total**
Roller chain, ANSI #40, 10 ft	Grainger 2W093 [4]	$23.65	8	$189.20
Connecting links, ANSI #40, 5 ct.	Grainger 5X293 [4]	$3.72	1	$3.72
Sprocket, ANSI #40, 3.196″ diam.	Grainger 1L142 [4]	$17.25	1	$17.25
Idler sprocket, ANSI #40, 2.96″ OD	Grainger 5A551 [4]	$31.64	1	$31.64
Brakemotor, 2 HP, 1725 RPM, 3-ph.	Grainger 4TD99 [4]	$587.50	1	$587.50
Inline speed reducer, 20 : 1, 2 HP	Grainger 5YV07 [4]	$412.25	1	$412.25
Motor switch, 3-ph, indoor	McM-C 7657K42 [5]	$46.98	1	$46.98
Drawbar spring, $8\,3/4''$	McM-C 9630K2 [5]	$15.26	2	$30.52
$3\,11/16''$ turnbuckle, 215 lb WLL	McM-C 30125T603 [5]	$2.43	2	$4.86
$1\,1/2''$ Sch. 40 pipe flange, unthr.	McM-C 68095K134 [5]	$8.84	2	$17.68
$5\,1/2'' \times 1\,1/2''$ Sch. 40 pipe nipple	McM-C 44615K163 [5]	$2.09	1	$2.09
Rigid caster, 4” diam., 800 lb.	Grainger 2G131 [4]	$18.32	40	$732.80
Total				**$2076.49**

Table 1: Required mechanical components

References

[1] T. P. Sullivan, “A laminated plywood turntable,” in *Technical Design Solutions for Theatre*, ser. The Tech Brief Collection, B. Sammler and D. Harvey, Eds. New Haven: Yale School of Drama, 1992, vol. 1.

[2] A. Holden, “A frameless turntable,” in *Technical Design Solutions for Theatre*, ser. The Tech Brief Collection, B. Sammler and D. Harvey, Eds. Woburn: Focal Press, 2002, vol. 2.

[3] A. Hendrickson, "Roller chain turntable drives," in *Technical Design Solutions for Theatre*, ser. The Tech Brief Collection, B. Sammler and D. Harvey, Eds. Woburn: Focal Press, 2002, vol. 2.

[4] Grainger, Inc. http://www.grainger.com/.

[5] McMaster-Carr, Inc. http://www.mcmaster.com/.

[6] W. O. Parker, R. C. Wolf, and D. Block, *Scene Design and Stage Lighting*, 8th ed., ser. Wadsworth Series in Theatre. Thomson-Wadsworth, 1990.

[7] R. L. Arnold, *Scene Technology*, 2nd ed. Englewood Cliffs: Prentice-Hall, 1990.

[8] J. M. Gilette, *Theatrical Design and Production: An Introduction to Scene Design and Construction, Lighting, Sound, Costume, and Makeup*, 2nd ed. Mountain View: Mayfield, 1991.

[9] A. Hendrickson, "A hand driven endless loop turntable drive," in *Technical Design Solutions for Theatre*, ser. The Tech Brief Collection, B. Sammler and D. Harvey, Eds. Woburn: Focal Press, 2002, vol. 2.

[10] P. Carter, *Backstage Handbook*, 3rd ed. Louisville, Kentucky: Broadway Press, 1994.

[11] A. E. Holden and B. J. Sammler, *Structural Design for the Stage*. Woburn: Focal Press, 1999.