SMDC 22
STAGE MACHINE DESIGN COMPETITION

2022 Clockworks

2022 Stage Machine Design Competition Design Proposal

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Design Specification

For this design project, the team has been hired to create a “crazy clock” effect for a production of *All in the Timing*. This effect will happen at a variety of times during the show, but primarily during scene shifts.

Performance

- The clock contains an hour, minute, and second hand that rotate on separate axes
- The movement of the hour hand should be dependent on the minute hand, and the movement of the minute hand should be dependent on the second hand
- Two movements:
  - First movement: All three clock hands will move in the clockwise direction, one rotation of the second hand will yield the minute hand to rotate six degrees, one full rotation of the minute hand will move the hour hand thirty degrees, the second hand’s velocity should be three revolutions per second, the starting and ending points of the hands do not matter, movement should last for one minute which would result in 180 full revolutions of the second hand, 1 revolution of the minute hand, and 180 degree movement of the hour hand
  - Second movement: The second and hour hands will move counterclockwise, the minute hand will move clockwise, one revolution of the second hand will make the minute hand move eighteen degrees, for each single revolution of the minute hand, the hour hand will move sixty degrees, the second hand should have an angular velocity of one revolution per second, the initial and final position of the hands does not matter, the movement should last for one minute which would include 60 full revolutions of the second hand, three revolutions of the minute hand, and a 180 degree movement of the hour hand.
- No artwork needs to be recreated on the face of the clock (numbers or spirals)
- The hands need to be mechanically driven, but not absolutely motorized
- Hand-driven systems are allowed
- Only one actuator can drive all three hands
- The scene shifts will involves music that adds ticking noises, the mechanism should be as quiet as possible
- There will be time to make adjustments to the clock to change the movement needed
- Teams will have twenty minutes to demonstrate both movements
- The time needed to make adjustments will be factored into the judge’s scoring

Cost

- There is no set cost for supplies, but that is something the team will work on to ensure enough money will be used to make the best solution to this design problem.
- $25 each to compete in the competition
- Starting with spending an additional $20 for supplies as deemed fit by the team later

Time

- Weekly meetings to create the project
- From January until May 7

Processes

- Basic carpentry and metalworking skills
- 3D Printing
- CNC routing
- Robotics–programming and implementation
- Electrical Engineering
- Soldering

Assembly

- The competition team will use the Purdue scene shop
- The competition will occur in the Hansen Theater.

Size

- 2' diameter circle

Weight

- Weight is up to us to ensure the clock can function properly during the show

Maintenance

- A pre-check and test of the clock is allowed prior to the competition demonstration

Packaging

- The clock will be constructed and stored in the scene shop and moved into the Hansen Theater on competition day

Testing

- Testing will be required throughout the competition to ensure that the mechanism will work as planned

Safety

- No pyrotechnics
- Do not have the hands spin too fast that it would be dangerous if flung off

Life Span

- The twenty minute demonstration window for the judges

Materials

- ⅛" plywood clock hand file will be provided for each team to create
- Anything else the team deems necessary to purchase

Concept Designs

Initial Findings

Before diving into the initial concept design phase, the team met to do group research for forty minutes to brainstorm any possible ideas related to how to solve this design challenge. The team members divided the challenge into three main parts: actuators, power transfer, and direction change. Here a wide variety of ideas were explored including electric motors, gears, chain and sprockets, and interchangeable pieces. Inspiration for a majority of the team's concept design ideas came from an online version of Henry Brown's *Five Hundred and Seven Mechanical Movements*. From these baseline ideas, the team dove into further research to decide on the best design path moving forward.

Sub Concepts

Actuators

1. Electric Motor
   How it works:
   - Electricity powers motor to drive motion of clock

   Pros:
   - Can program to control speed consistently
   - Can use tachometers/encoders to control speed
   - Variable, but controllable, speed
   - Some experience among team members

   Cons:
   - Could impact material choices
   - Could be more complicated than other options
   - High cost

2. Air Motor
   How it works:
   - Compressed air within the motor drives motion of clock

   Pros:
   - Consistent
   - Doesn't require major programming
   - Variable, but controllable, speed

Cons:

- No one on the team has experience with them, so would require extra research
- Might be loud
- High cost

3. Hand Crank

How it works:

- User manually turning crank drives motion of clock

Pros:

- Low cost
- Simple design
- Less points of failure
- Variable, but controllable, speed

Cons:

- Potentially inconsistent

4. Counterweights

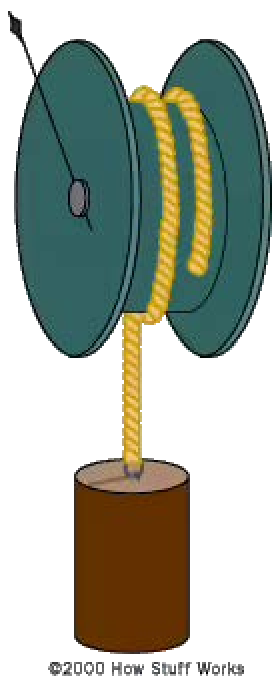

Figure 1.1: Counterweight System Diagram (https://electronics.howstuffworks.com/gadgets/clocks-watches/clock2.htm)

How it works:

- Counterweight is raised to store energy
- When released, downward motion of the counterweight drives motion of clock

Pros:

- Consistent

Cons:

- One speed
- Hard to fit behind the clock face
- Heavy

5. Springs

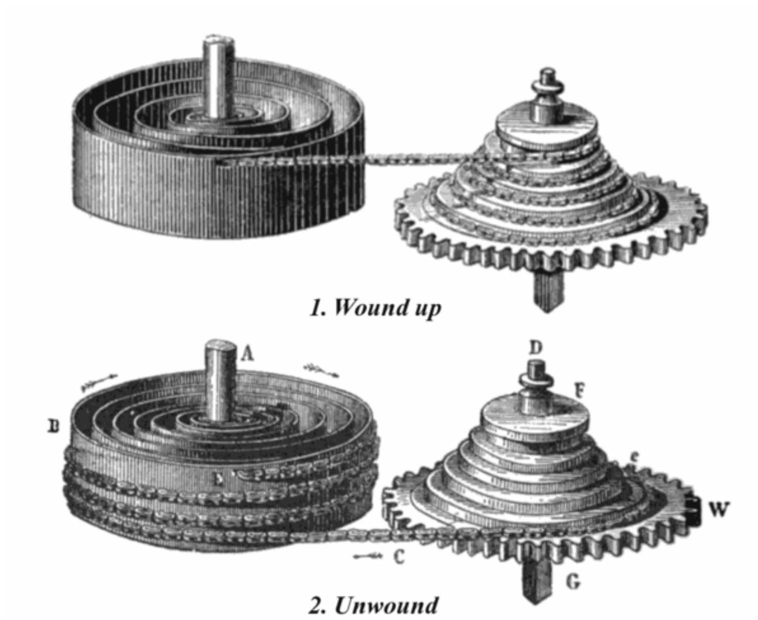

Figure 1.2: Clock Spring System Diagram (https://en.wikipedia.org/wiki/Fusee_(horology))

How it works:

- Spring is wound up to store energy
- When released, spring imparts energy to motion of clock

Pros:

- Consistent?

Cons:

- One speed
- Potential safety issue
- Harder to implement

Power Transfer

1. Gears

   How it works:

   - Gears with interlocking teeth transfer power between them
   - Speed can change depending on gear ratios

Pros:

- Can use prefabricated gears
- Can also 3D print or use CNC router to make gears
- Can control gear ratios to change speed between clock hands
- Teeth interlock, so slipping is not an issue

Cons:

- How to change direction?
- Pinch points

2. Friction Wheels

   How it works:

   - Friction in between adjacent wheels transfers power between them

   Pros:

   - Can control ratios to change speed between clock hands
   - Can make our own

   Cons:

   - Slipping is a possibility, so less consistent
   - Possible difficulty in changing direction
   - Pinch points

3. Linkage

   How it works:

   - Turns linear power into rotational

   Pros:

   - Interesting challenge
   - Could use linear actuator

   Cons:

   - Don’t know how to implement
   - Hard to fit behind the clock face

4. Chain & Sprocket

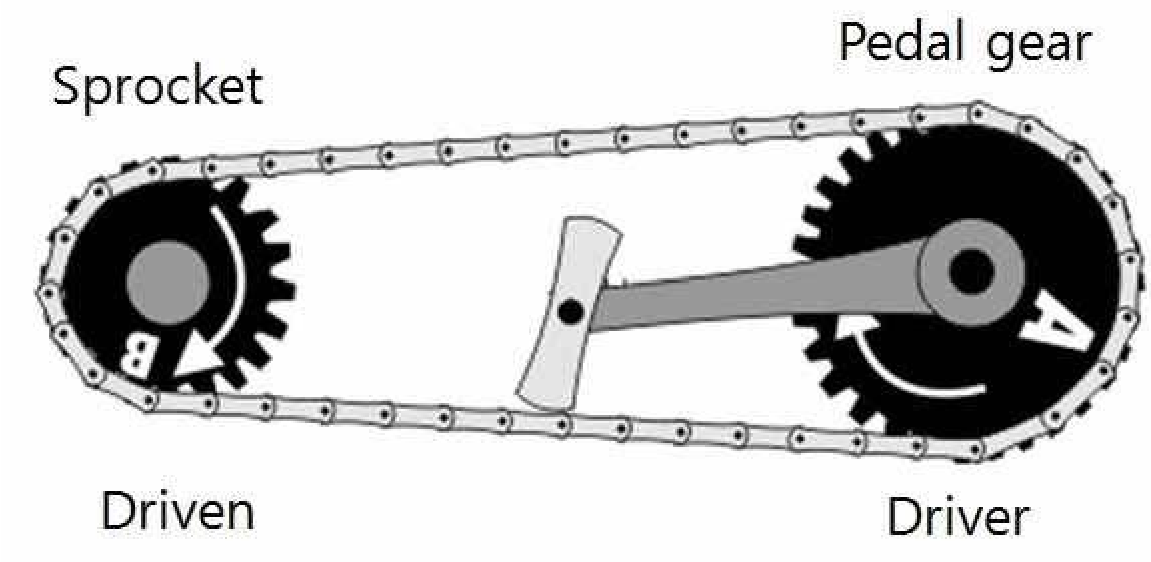

Figure 2.1: Chain and Sprocket Diagram
(https://www.fomshop.ml/products.aspx?cname=chain%2Bsprocket%2Bfor%2Bbike&cid=43.)

How it works:

- Chain is held together by pins and a master link
- Rotates around gears just like a bike chain
- Higher torque and RPM requires a larger distance between the links (Convergence3dVideos)

Pros:

- Easy math
- Fewer pinch points
- Easy to change to different speeds similar to a bike chain
- Potentially use bike hub parts
- Chain cannot slip on the sprocket (Lipot)

Cons:

- Size issue to fit within the system
- Under tension and could be difficult to implement
- Need chains (more to buy)
- Can be loud

5. Pulleys & Belts

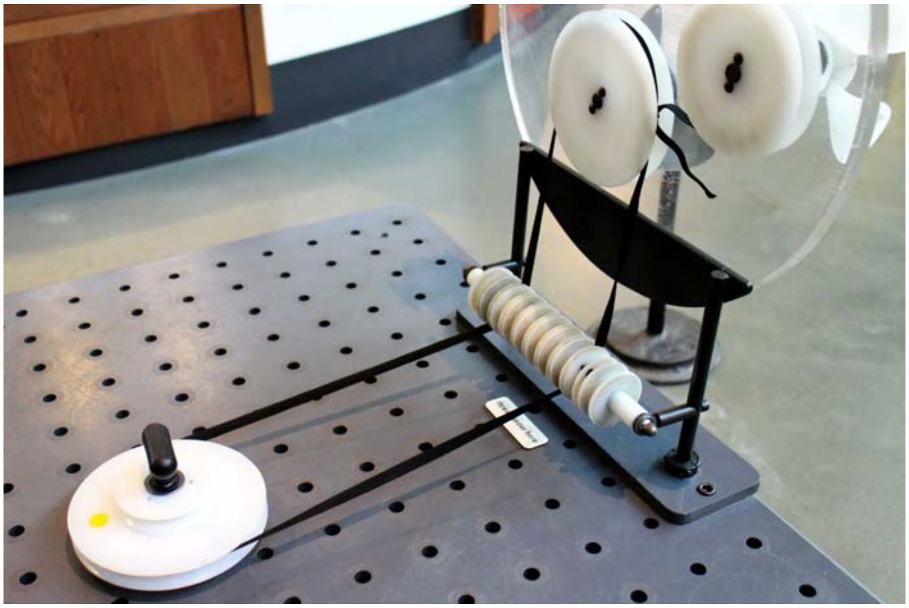

Figure 2.2: Sample Pulley Device
(https://www.instructables.com/Basic-Pulley-Mechanisms/.)

How it works:

- Use of wheels and ropes to give a device a mechanical advantage to complete the desired task

Pros:

- Easy math similar to the gears concept
- Fewer pinch points
- Can be 3D printed
- Easy to interchange parts
- Simple assembly

Cons:

- Size and reliability issue should the pulley get off its track
- Pulley could break from tension as it rotates through the motions
- Pulley would be under tension and difficult to implement
- Would need additional belts (more to buy)

Direction Change

1. Interchangeable Parts

How it works:

- Replacing a gear or other part to lead to a direction change
- Adding an additional part to the gear train that would create a change in direction

Pros:

- Easy to implement
- Easy to test
- Easy to make or build

Cons:

- Potentially long changeover time
- Could make an error in the changeover that would cause the device to not function

2. Lever/Switch

How it works:

- Pulling a lever or moving a switch to change the direction of motion
- Similar to an on/off switch, but instead a direction 1/direction 2 switch

Pros:

- Quick change over
- Most consistent
- Could be mechanical or electrical

Cons:

- Harder to implement within the system
- Requires more electrical/coding skills than the team's comfort ability

3. Reversible Drive

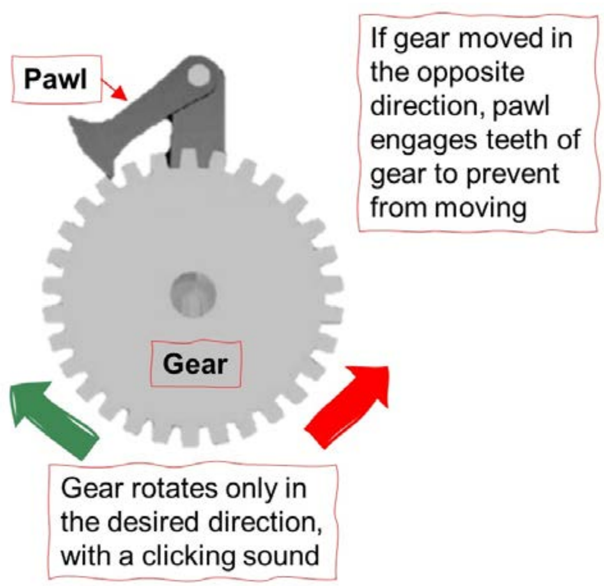

Figure 3.1: Ratchet's Functionality

(https://www.tien-i.com/blog_detail/29-ratchet-handle-design-standard-round-head.)

How it works:

- Motorizing a pawl that connects to the gear so that one motion will be prevented while the other occurs

Pros:

- Quick changeover
- Interesting mechanics
- Useful in rotary one-directional motion ("Pawl and Ratchet")

Cons:

- Hardest implementation
- Involves more components that could individually fail which would limit the performance of the design

Concept Evaluation

Actuator	Ease of Implementation	Reliability	Cost	Aesthetic	Elegance of Solution	Ease of Operation	Consistency of operation	Weight	Meets Requirements	Volume	Safety	Total
Electric Motor	0	0	0	0	0	0	0	0	0	0	0	0
Hand Crank	5	5	3	0	-3	-3	-3	-1	0	0	0	31
Air Motor	-5	0	1	0	1	0	0	0	0	-1	0	-24

Actuator	Ease of Implementation	Reliability	Cost	Aesthetic	Elegance of Solution	Ease of Operation	Consistency of operation	Weight	Meets Requirements	Volume	Safety	Total
Electric Motor	-3	-1	-2	0	3	3	4	0	0	0	0	6
Hand Crank	0	0	0	0	0	0	0	0	0	0	0	0
Air Motor	-5	-1	-2	0	4	2	0	0	0	-1	0	-29

Actuator	Ease of Implementation	Reliability	Cost	Aesthetic	Elegance of Solution	Ease of Operation	Consistency of operation	Weight	Meets Requirements	Volume	Safety	Total
Electric Motor	1	1	1	0	-2	1	0	0	0	1	0	17
Hand Crank	5	1	3	0	-4	-3	-2	0	0	0	0	16
Air Motor	0	0	0	0	0	0	0	0	0	0	0	0

ACTUATOR TOTALS	
Electric Motor	23
Hand Crank	47
Air Motor	-53

Power Transfer	Ease of Implementation	Reliability	Cost	Aesthetic	Elegance of Solution	Ease of Operation	Consistency of operation	Weight	Meets Requirements	Volume	Safety	Total
Gears	0	0	0	0	0	0	0	0	0	0	0	0
Chain + Sprocket	-1	-1	-2	0	0	0	0	-2	0	2	-1	-17
Linkage	-4	-1	0	0	1	0	-2	-1	0	0	0	-35
Friction Wheels	0	0	-1	-2	-1	0	-1	0	0	3	0	-2
Pulleys + Belts	-1	-2	-1	-1	0	0	-1	0	0	1	0	-21

Power Transfer	Ease of Implementation	Reliability	Cost	Aesthetic	Elegance of Solution	Ease of Operation	Consistency of operation	Weight	Meets Requirements	Volume	Safety	Total
Gears	2	0	1	-1	1	0	0	1	0	-1	0	11
Chain + Sprocket	0	0	0	0	0	0	0	0	0	0	0	0
Linkage	-3	-1	0	1	1	0	-2	0	0	0	0	-28
Friction Wheels	0	-1	1	-1	0	0	-1	1	0	2	0	-1
Pulleys + Belts	-1	-1	0	-1	0	0	-1	1	0	1	0	-12

Power Transfer	Ease of Implementation	Reliability	Cost	Aesthetic	Elegance of Solution	Ease of Operation	Consistency of operation	Weight	Meets Requirements	Volume	Safety	Total
Gears	5	2	0	0	0	1	2	0	0	0	0	48
Chain + Sprocket	3	0	-2	0	0	1	1	-1	0	1	0	19
Linkage	0	0	0	0	0	0	0	0	0	0	0	0
Friction Wheels	2	0	0	0	-1	1	1	0	0	1	0	20
Pulleys + Belts	2	0	-1	-1	0	1	1	0	0	1	0	17

Power Transfer	Ease of Implementation	Reliability	Cost	Aesthetic	Elegance of Solution	Ease of Operation	Consistency of operation	Weight	Meets Requirements	Volume	Safety	Total
Gears	1	2	1	0	0	1	2	0	0	-1	0	28
Chain + Sprocket	1	2	-2	0	0	1	2	-2	0	-2	0	14
Linkage	-3	1	0	0	1	0	0	0	0	-1	0	-12
Friction Wheels	0	0	0	0	0	0	0	0	0	0	0	0
Pulleys + Belts	0	0	-1	0	0	1	1	0	0	1	0	8

Power Transfer	Ease of Implementation	Reliability	Cost	Aesthetic	Elegance of Solution	Ease of Operation	Consistency of operation	Weight	Meets Requirements	Volume	Safety	Total
Gears	1	2	2	0	0	1	3	0	0	-2	0	33
Chain + Sprocket	1	2	-1	0	0	1	3	-2	0	-1	0	25
Linkage	-3	1	0	0	1	0	1	0	0	-1	0	-7
Friction Wheels	1	1	1	0	0	0	0	0	0	1	0	16
Pulleys + Belts	0	0	0	0	0	0	0	0	0	0	0	0

Power Transfer Total	
Gears	##
Chain + Sprocket	41
Linkage	-82
Friction Wheels	33
Pulleys + Belts	-8

Figure 4.1: Matrices comparing scores for actuators and power transfer schemes

WDM 1: Actuator	Difficulty of Implementatio	Reliability	Low Cost	Aesthetic	Elegance of solution	Ease of Operation	Consistency of Operatio	Weight	Meets Requirement	Volume	Safety	Total
Count	5	5	3	1	1	3	5	1	5	3	5	X
Electric Motor	0	0	0	0	0	0	0	0	0	0	0	0
Hand Crank	-1	-3	2	0	0	0	-3	0	0	-1	0	-32
Air Motor	-1	0	0	0	0	0	0	-3	0	-5	0	-23
Counterweights	-3	-1	0	-3	0	0	0	-1	0	-1	-1	-32
Springs	0	-1	1	0	0	0	-1	0	0	-1	-1	-15

WDM 2: Actuator	Difficulty of Implementatio	Reliability	Low Cost	Aesthetic	Elegance of solution	Ease of Operation	Consistency of Operatio	Weight	Meets Requirement	Volume	Safety	Total
Count	5	5	3	1	1	3	5	1	5	3	5	X
Electric Motor	3	5	0	1	0	3	0	0	0	-1	3	62
Hand Crank	1	-1	1	-1	1	0	-3	0	0	0	0	-12
Air Motor	1	-1	0	-3	0	0	-1	0	0	-1	0	-11
Counterweights	-3	0	-1	-3	0	0	0	0	0	-3	0	-30
Springs	0	0	0	0	0	0	0	0	0	0	0	0

WDM 1: Power	Difficulty of Implementatio	Reliability	Low Cost	Aesthetic	Elegance of solution	Ease of Operation	Consistency of Operatio	Weight	Meets Requirement	Volume	Safety	Total
Count	5	5	3	1	1	3	5	1	5	3	5	X
Gears	3	0	3	3	0	0	0	1	0	0	-3	13
Friction Wheels	0	0	-1	0	0	0	-1	0	0	1	-1	-10
Linkage	-3	0	-1	0	1	0	0	-1	0	0	-1	-23
Chain and Sprocket	0	0	0	0	0	0	0	0	0	0	0	0
Pulleys and Belts	-2	0	-1	0	-1	0	0	-1	0	0	0	-15

WDM 2: Power	Difficulty of Implementatio	Reliability	Low Cost	Aesthetic	Elegance of solution	Ease of Operation	Consistency of Operatio	Weight	Meets Requirement	Volume	Safety	Total
Count	5	5	3	1	1	3	5	1	5	3	5	X
Gears	0	0	0	0	0	0	0	0	0	0	0	0
Friction Wheels	-2	0	0	0	0	-1	0	0	0	2	1	-2
Linkage	-3	0	-3	0	-1	-1	0	0	0	-1	0	-31
Chain and Sprocket	-3	0	-3	0	-1	0	0	0	0	-1	0	-28
Pulleys and Belts	-3	0	-4	0	-1	-1	0	-1	0	-1	0	-33

WDM 1: Direction	Difficulty of Implementatio	Reliability	Low Cost	Aesthetic	Elegance of solution	Ease of Operation	Consistency of Operatio	Weight	Meets Requirement	Volume	Safety	Total
Count	5	5	3	1	1	3	5	1	5	3	5	X
Interchangeable Parts	3	3	1	-2	0	0	0	0	0	0	-1	26
Lever/Switch	-2	0	-1	0	0	0	0	0	0	0	0	-13
Reversible Drive	0	0	0	0	0	0	0	0	0	0	0	0

WDM 2: Direction	Difficulty of Implementatio	Reliability	Low Cost	Aesthetic	Elegance of solution	Ease of Operation	Consistency of Operatio	Weight	Meets Requirement	Volume	Safety	Total
Count	5	5	3	1	1	3	5	1	5	3	5	X
Interchangeable Parts	0	0	0	0	0	0	0	0	0	0	0	0
Lever/Switch	-1	0	-1	0	0	1	0	0	0	0	0	-5
Reversible Drive	-3	0	-1	0	0	0	0	0	0	-1	0	-21

Figure 4.2: Matrices for actuators, power transfer, and direction change

After combining team members' decision matrices, the team settled on an electric motor as an actuator, gears for power transfer, and interchangeable parts for the change between the motions. These were chosen for their ability to achieve the performance required by the contest, their ease of operation, and the viability of their implementation given the skills of the team.

Cost Estimate

Item	Number	Cost	Link
Arduino Uno Microcontroller	1	23.00	https://store-usa.arduino.cc/products/arduino-uno-rev3/
Arduino Compatible Motor Driver	1	9.95	https://www.pololu.com/product/2999
50:1 Reduction 12V Motor w/Encoder	1	39.95	https://www.pololu.com/product/4753
Stamped Aluminum Motor Bracket	1	7.95	https://www.pololu.com/product/1084
2'x4'x¼" AC Plywood	1	15.79	https://www.menards.com/main/building-materials/panel-products/handi-panels/2-x-4-acx-sanded-plywood-handi-panel/1251243/p-1444425371789.htm
2" Machine Screws, Washers, Nuts		0.00	Pulled from Purdue Stock

Implementing the Design

The limiting factor in the concept design is the number of gears required to achieve the reduction from the second hand to the minute hand and minute hand to hour hand. This calls for a motor powerful enough to overcome the force of friction introduced by several gears.
A motor that is geared down 50:1 will help give the required torque. Its top rotational speed is 200 RPM; an Arduino Microcontroller, motor driver, and the encoder integrated in the motor will regulate its speed. We will set our motor speed to 180 RPM to drive the second hand directly, and pull power off of the shaft to drive the gear reduction to the other hands.

The clock and gears will be made from plywood using Purdue's Shopbot CNC router. Using involute pattern gear teeth to transfer speed and torque predictably even as the difference between gear centers changes will alleviate the problem of wood's dimensional instability. Sanded plywood for the gears will reduce friction caused by the gears rubbing against the clock face.

The gear train will be mounted in gearing groups on interchangeable frames that disconnect quickly from the back of the clock. This will reduce time spent changing over between motions.

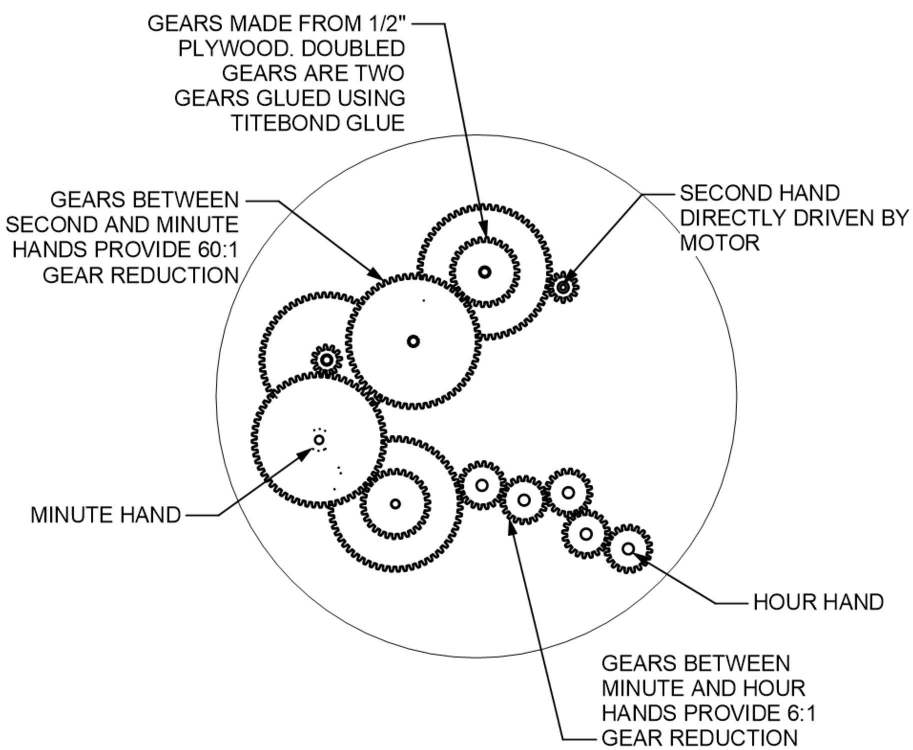

Figure 4.3: Concept sketch for movement 1

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