Swinging Spider Electronic Adjustment Project

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1. Summary

TH Fabrication manufactures the Swinging Spider cultivator, an improvement on other cultivators in that it is adjustable. One of its row units is depicted to the right - several of these attached to a tool bar comprise a cultivator, which is then mounted to a tractor's three-point hitch.

This design is already adjustable by hand, but some operators desire faster changeovers, even changing while the machine is running. To this end, we would like to develop an actuation system for the adjustments of the cultivator.

Some potential options and concepts are considered here along with estimates of their costs.

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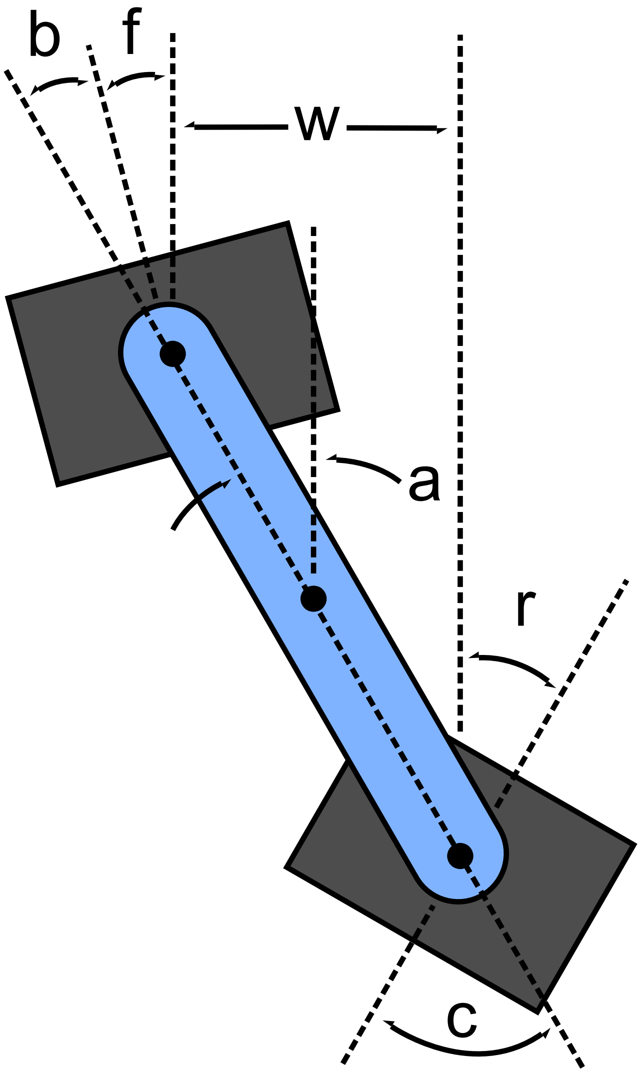
2. Technical Description of Existing System

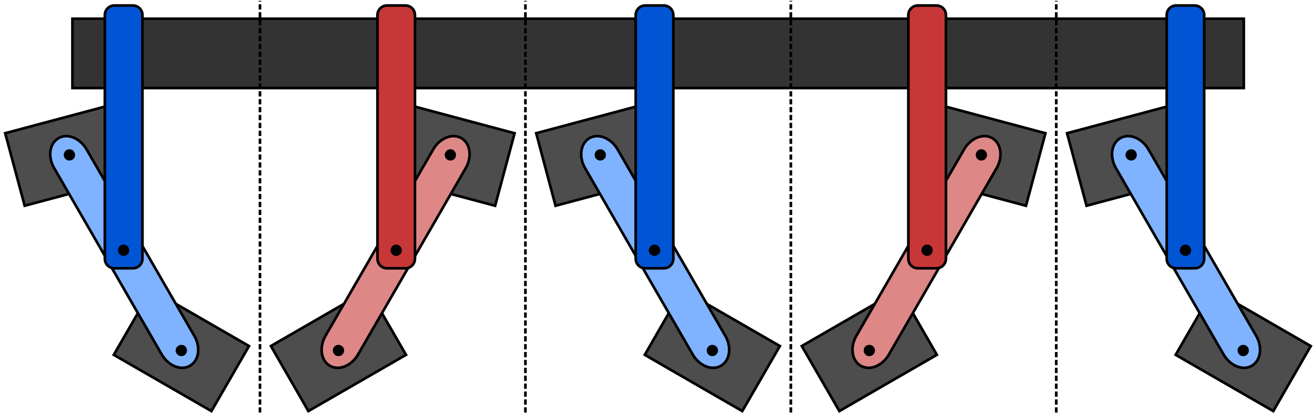
A top view of a row unit is shown below. Currently, TH Fabrication's cultivators can be adjusted in three ways per row unit:

- **w**: width of cultivation (by varying **a**, the angle of the arm.)
- **f**: angle of the front wheel (by varying **a** and **b**, angle between arm and wheel)
- **r**: angle of the rear wheel (by varying **a** and **c**, angle between arm and wheel)

For the sake of clarity, angles f and r will be referred to as "field-centric wheel angles". Angles c and b will be "arm-centric wheel angles".

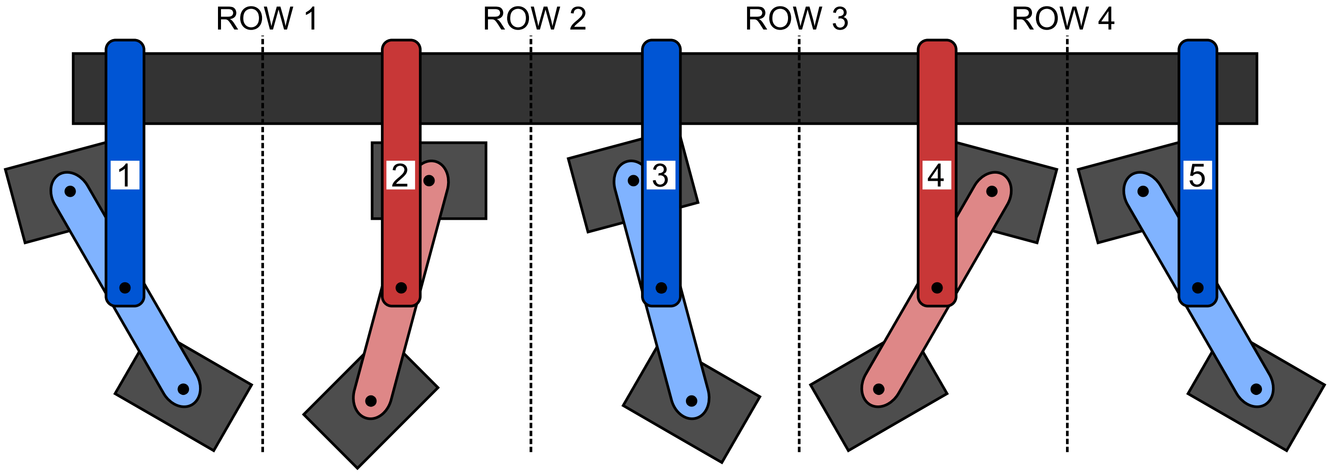


A cultivator consists of several row units installed alongside each other. An exemplary four-row cultivator (consisting of five row units) is shown below.



Note that every other row unit has its arm angle alternating. This is to balance forces and build residue mounds on crop more effectively.

An operator can adjust each row unit independently, but this has its limitations, as demonstrated below.



Here, row unit 2 has been adjusted by simply swinging the arm (a). Unit 3 has been adjusted by swinging the arm (a) and changing b and c so that the wheel angles f and r remain the same as before.

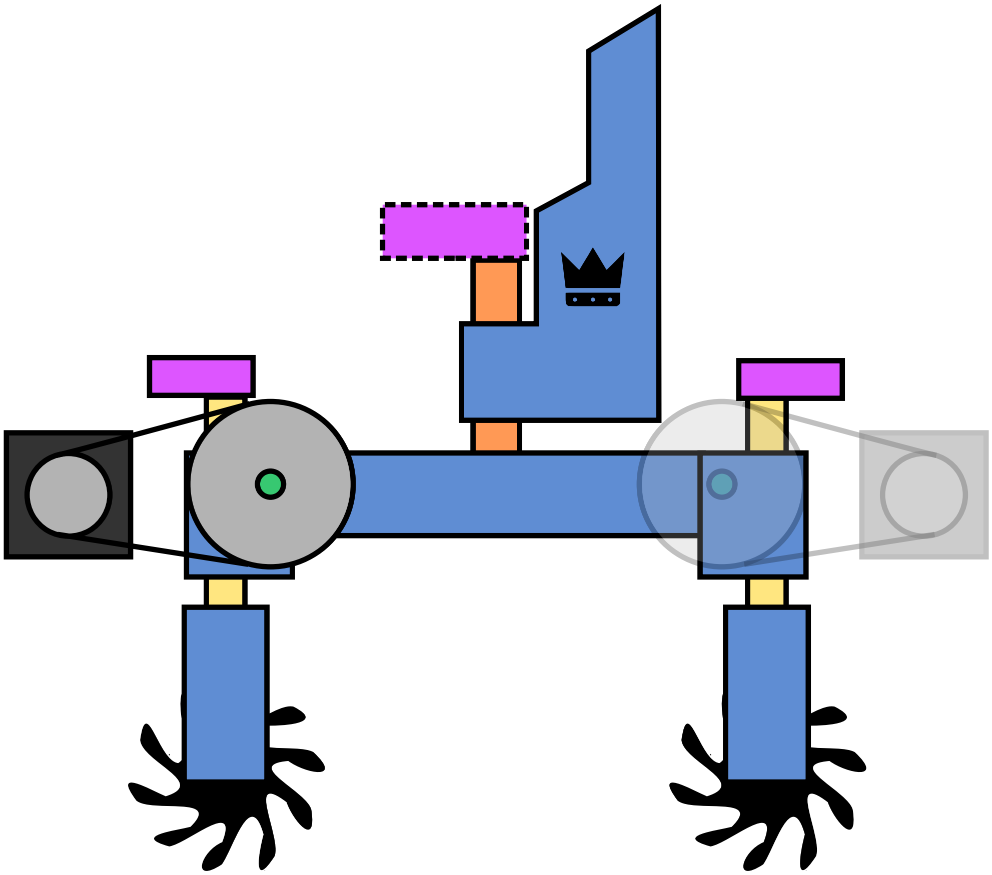
Although the operator may not have intended it, on row unit 2, the wheel angles (f and r) have changed.

Note that on rows 1 and 3, the distance between the wheel and row is different on the left and right sides of each. This is because the cultivator width for the row units is set differently. There is no mechanical provision to change this and have the rows centered in the current design. [See Section 7 - Questions]

3. Proposed Architecture - Direct Electrical Actuation

3a. Wheel Actuators and Sensing

The worm-and-wheel design of the TH Swinging Spider is already known to be durable enough in real-world use. Undermining the integrity of this design would require re-vetting all affected components. Thus, it seems best to use these existing components.



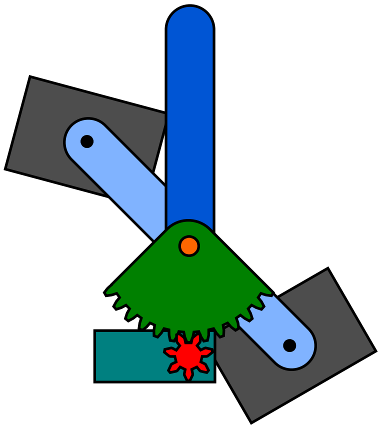
Wheel angle can be adjusted by attaching a motor to the existing hand crank shaft. It is likely helpful, for packaging reasons, that a chain, belt, or gear drive be used between the crank shaft and motor. A rotary position sensor (pink) is mounted to each wheel pivot axle (yellow), enabling closed-loop control of the wheel headings (and thus, synchronization between all row units). If this sensor was an absolute position sensor (e.g. potentiometer), the heading of the wheels would be readily known without a homing sequence upon system startup.

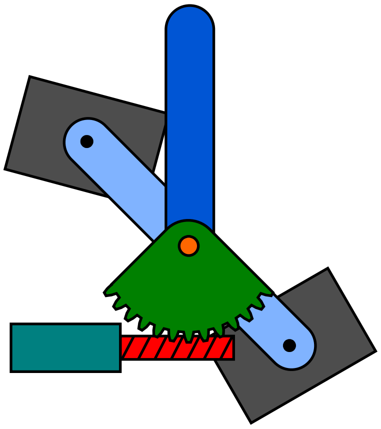
Even if the arm is not actuated, a position sensor could be placed on the arm pivot axle to know its position. This would allow the operator to manually change the arm to a new position and have the wheels automatically re-align themselves to the correct heading.

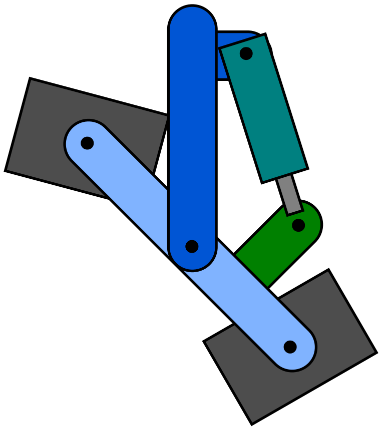
3b. Arm actuator concepts

The torques on the arm pivot are much higher than on the wheel pivots. Designing an actuator for this motion will require testing of the mechanical components for durability. It is probably best that whatever actuator used be self-locking (like the worm-and-wheel of the wheel actuator).

I entertained three concepts at first (all of which use the same arm rotary sensor described previously):







3bi. Sector Gear

This concept uses a sector gear mounted to the arm pivot shaft, above the pivot bearing. The gearmotor (teal) used here must be a self-locking one (tarping motors seem like good candidates).

This gear should have large enough teeth to be unaffected by debris.

3bii. Sector Worm Gear

This concept uses a sector gear mounted to the arm pivot shaft, above the pivot bearing, but the gear would be a worm wheel. A motor drives a worm gear which drives the sector gear.

Both of these sector gears have a substantial problem: they rely on the pivot axle to transmit and resist torques. This is stress that has not been vetted – so could result in failure of the shaft.

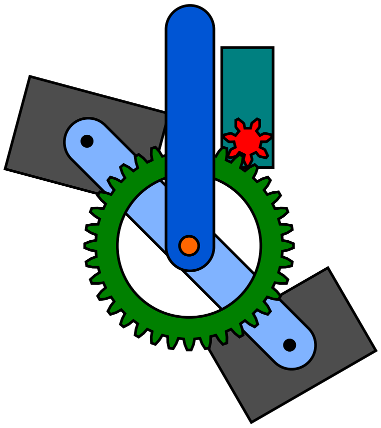
These sector gears also limit the motion of the arm to +/- 45 degrees, which may not be enough.

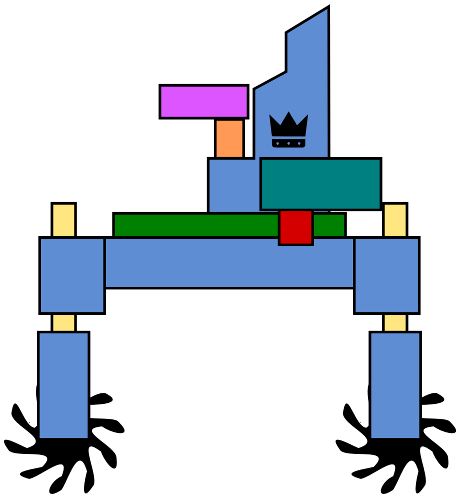
3biii. Linear Actuator

This concept uses a linear actuator mounted between the body of the row unit and the arm. This linear actuator could be electric or hydraulic.

3biv. Underside Ring Gear

This concept places a gear underneath the pivot point and main body of the row unit.





The gear could be made out of two pieces if needed. It could even be a chain-and-sprocket.

The motor must be self-locking.

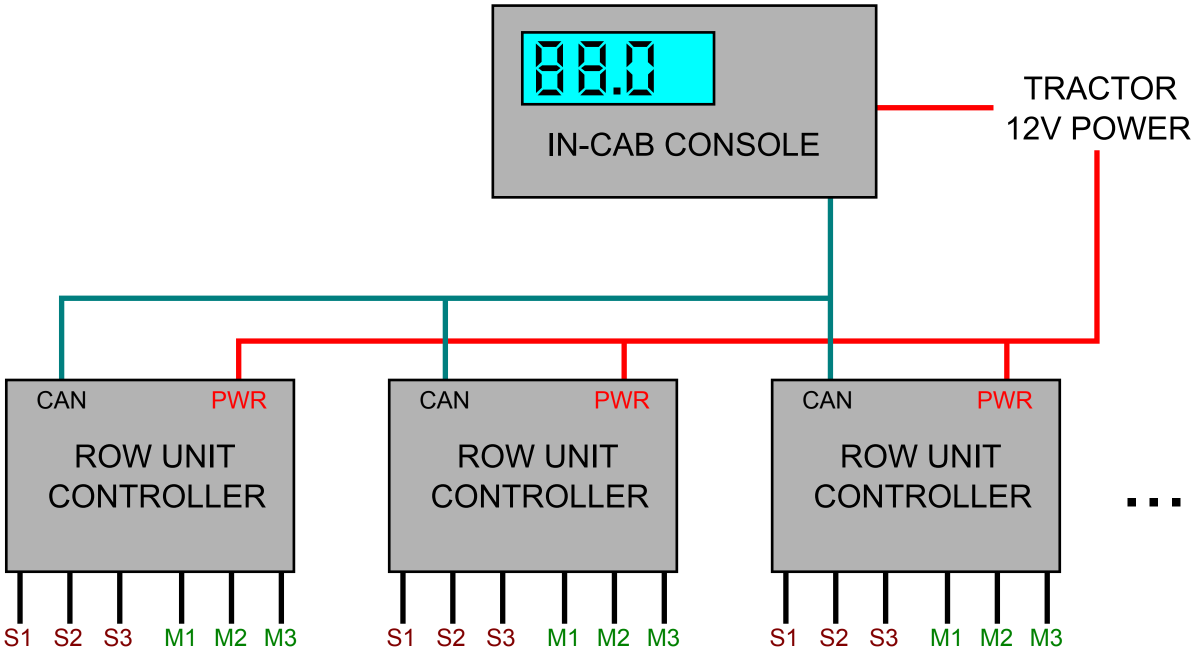
This concept avoids torques on the arm pivot.

This design may impede on attachments.

I think this concept for arm actuation is the most promising, even if it is not as readily integrated as the others.

3c. Row Unit Control

The electrical system would consist of two main types of module: an in-cab user interface, and row unit controllers.



Row Unit Controllers would receive commands for target positions over a CAN (Controller-Area-Network) Bus. They would also be able to report their status back to the in-cab console in this fashion.

Row Unit Controllers would control the actuators based on commanded position and actual sensed position.

A Row Unit Controller may have the following components inside of it:

- A microcontroller capable of communicating on a CAN Bus
- 3 motor controllers
  - These are probably simple H-bridge relays – a low-cost option capable of handling high currents but may require some engineering effort to create a board
  - These might be more sophisticated motor controllers – higher cost, but allowing variable speed control, and requiring less engineering effort. These motor controllers may be able to handle the reading of sensors directly.
- Auto-resetting breakers
- A programming port or set of DIP switches to configure the row unit (homing sensors, setting zone, setting even-odd orientation)

The Row Unit Controller should be in a water- and dust- proof enclosure, preferably mounted to the tool bar with isolation mounts.

Other additions (like flip-up units) may make sense to be controlled by the Row Unit Controller.

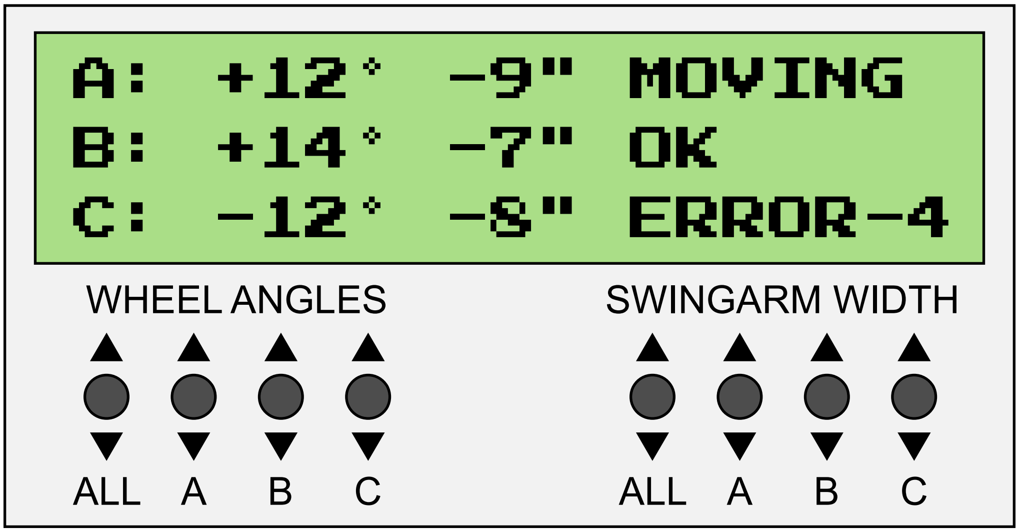
It may be possible to have these controllers control multiple row units, but I doubt that the cost savings will be substantial.

There are controllers like the BasicMicro MCP233 (https://www.basicmicro.com/MCP233-Dual-30A-34VDC-Advanced-Motor-Controller_p_39.html) that are available off the shelf with analog input, dual output, and CAN Bus functionality – this may be a perfect candidate for a row unit controller or a shared one, but more research and testing will be required to determine this.

At the same time, simple motor controllers like these are plentiful and vetted for automotive and agricultural environments: https://www.tractorsupply.com/tsc/product/buyers-products-forward-and-reverse-relay-module-5541100-2344553

3d. User Interface

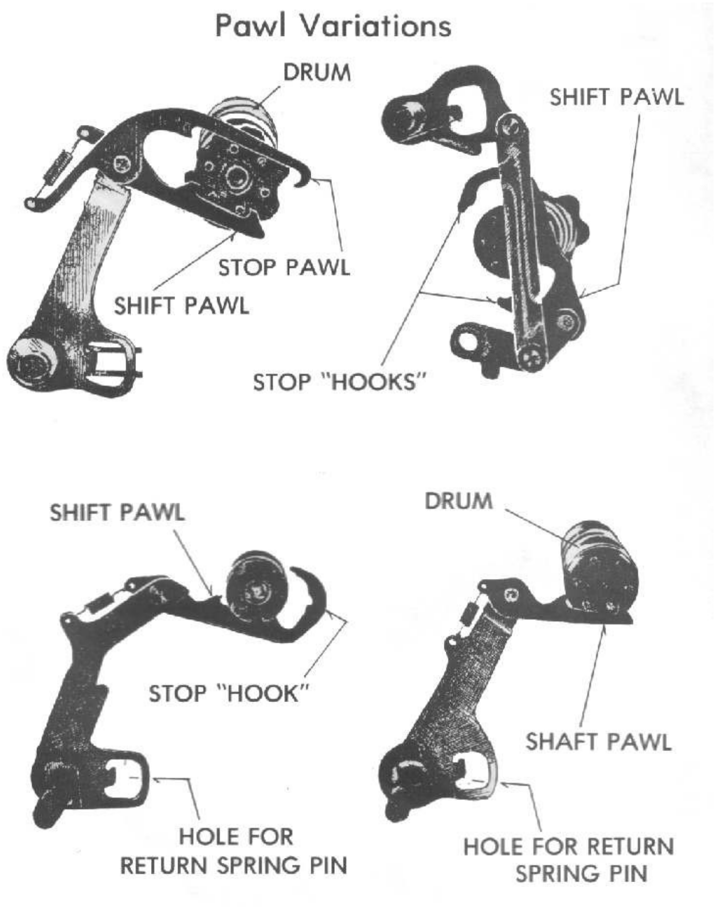
The in-cab user interface would have switches to change the angle and width settings. A screen displaying the current settings and statuses would be helpful. The diagram below shows a very rough example of what such a console could look like. The display could be as simple as an LCD panel, but other options exist as well.



While all row units can be commanded independently, I struggle to see how a user interface would be made that makes this more of a help than a hassle. More software would need to be written as well. A few zones seem much easier to control.

4. Alternative Concept – Incremental Operation

After sketching out the previous fully-electric design, I remembered about sequential gearbox shifters. These employ a sort of bi-directional ratchet. There are a number of variations on the concept as shown in the image to the right, and are often found in motorcycle and 4-wheeler engines.



See http://www.dansmc.com/gearshifters.htm for some more pictures.

The idea is that an input motion of sufficient range will cause a predictably consistent, incremental change in rotary position.

While such a mechanism is normally actuated by a person, it could be actuated electronically, pneumatically, or even hydraulically.

Such a ratcheting mechanism could be affixed to the adjustment shaft of the wheel angle quite readily. Such a ratcheting mechanism could also be affixed to a ring gear on the swingarm as discussed in section 3biv.

Pneumatic cylinders could be ganged together quite easily here; removing the need for individual row unit controllers in favor of a centralized bank of solenoid valves.

This would allow for varying levels of control.

Ultimately, while such a system in could be in theory simpler (as pneumatic actuators could be plumbed together and always kept in sync), in practice, it could result in erroneous actuation leading to de-synchronization of the various row units, or a system just as complex as the electrical one to monitor and correct for desyncing.

5. Alternative Concept – Hydraulic Swingarm Changeover

The concepts in section 3b for adjusting the swingarm position could be actuated with the tractor's hydraulic system. They would need to be plumbed (or attached) in an alternating fashion (even-odd row angles). To enable consistent behavior across all rows, adjustable hard stops would be employed. This would not allow for adjustability of row units, but it would allow for quickly changing over the swingarm position. This could work in conjunction with, or independent of, a wheel angle positioning system.

6. Questions and Comments

Many questions have arisen while writing this proposal (and more will come):

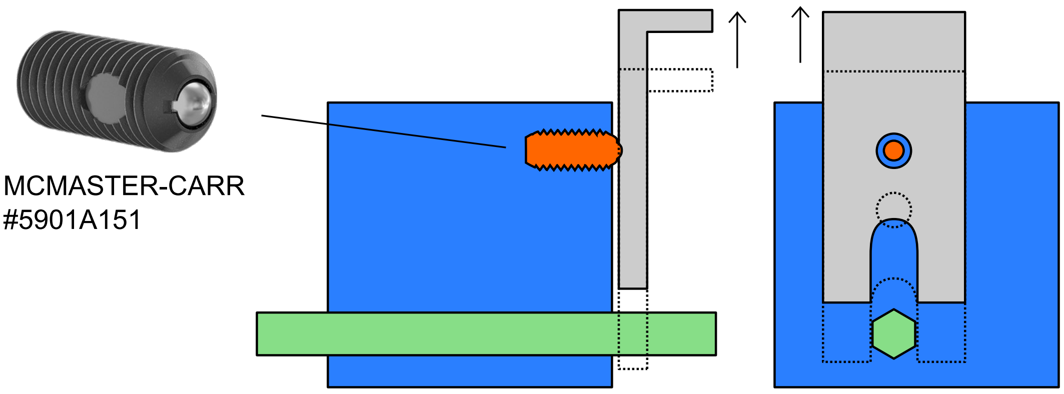
1. What range of travel is desired for each actuator?
2. Will swingarms always be in an alternating pattern?
3. What happens to wheels on the ends of a cultivator bar? Videos show these in the straight-ahead position. Should these be actuated?
4. Are there estimations or test data of forces that must be withstood by mechanisms?
5. What speed of change-over is required? Faster requires a more expensive motor, controller, and may even be too much for the electrical system of the tractor. What current can we draw from a tractor?
    1. If currents are too high, we may need to consider if a system that can change or adjust only a few units at a time is a reasonable compromise.
6. We can have row control units have auxilary outputs for future additions (e.g. downforce) – should we design a few of these into the electronics ahead of time?

A few comments as well:

1. Whether the adjustments to position can be made while driving will be a question of the forces seen by a cultivator – if they are very high, more expensive actuators will be required. Testing will be required to determine this.
2. Production PCB Design is not my forte! If any custom circuits are required (I think this is likely), we will want to talk to a manufacturer/supplier. ACC Electronix in Normal comes to mind. They may also be able to help with harnesses, enclosures, and maybe even assembly and programming.

7. Errata - Clip Locking

A drawing of a potential wheel angle adjustment locking clip improvement is shown below.



Already, the locking clip (grey) slides up and down to lock the hex shaft (green) in 60 degree increments. Now, a hole is added to the slide which interfaces with a spring-loaded ball detent. This holds the clip up and out of the way so that the hex shaft can rotate for adjustment. Now, the user can rotate the hex shaft with only one hand, before sliding the clip back down to lock the hex shaft in position.

8. Cost Estimation

After writing these concepts out, I have come up with a few “levels” for this package:

1. Both wheels and swingarm actuated
2. Only wheel angle actuated
3. Wheel angle actuated, with no zone control
4. Wheel angle actuated, with a hydraulic change-over mechanism as described in section 5

In addition to estimating material costs for a finished product (green boxes), I broke the engineering efforts down into three stages (blue boxes):

1. Development of the **mechanical** components (including the motors, but not including drives or sensors)
2. Development of **electrical** components (including software)
3. **Finalization** of these prototypes into a design suitable for production and manufacture

I intend at each stage to have a functional prototype which can be tested in the field in some fashion.

I hope this is a useful starting point for further discussion – I look forward to discussing this project further!

Wheels & Swingarm Actuated

Wheel Actuators (Per row unit)		
Component	*Cost*	*Qty*
Brackets, Hardware	$50	1
Gearmotor	$100	2
Driveline (Pulley, gears, e	$80	2
Sensor	$70	2
Cables	$10	4
	Totals	$590

Swingarm Actuator		
Component	*Cost*	*Qty*
Brackets, Hardware	$50	1
Gearmotor	$250	1
Driveline (Pulley, gears, e	$120	1
Sensor	$70	1
Cables	$10	2
	Totals	$510

Row Control Unit (RCU)		
Component	*Cost*	*Qty*
Housing	$10	1
Cables	$15	2
Connectors	$4	10
Microcontroller	$30	1
Motor Controller	$60	3
	Totals	$290

Operator Interface (OI)		
Component	*Cost*	*Qty*
LCD Panel	$50	1
Microcontroller	$100	1
Housing	$40	1
Connectors	$4	3
Cables	$15	3
Switches	$1	10
	Totals	$257

Mechanical Prototype	***Matl's***	***Eng. Hrs***
Understand basic force requirements		4
Specify Motors		4
Design Driveline		16
Build Prototype (1 row unit)	$1,650	12
Test & Refine Prototype	$800	20
	Total:	$6,930

Electrical Prototype	***Matl's***	***Eng. Hrs***
Specify Sensors		4
Design & Prototype RCU on Bench	$435	28
Design & Prototype OI on Bench	$514	28
Design Enclosures	$60	8
Build Prototype (1 row unit)	$547	20
Test & Refine Prototype	$200	30
	Total:	$11,196

Preparation for Production	***Matl's***	***Eng. Hrs***
Build 3 row unit cultivator	$6,641	12
Make Electrical Schematics		20
Make Mechanical Drawings		8
Handoff to Electrical Supplier(s)		25
Write Owner's Manual		20
	Total:	$13,441

Production Costs (Materials only - no assy, etc.)			
Base Cost	$257		
Per-row-unit cost	$1,390		
# of row units	3	13	25
Total System Cost	**$4,427**	**$18,327**	**$35,007**

Engineering Costs	***Rate***	***$80***	***/hr***
	Total Time	259	hr
	Eng. Labor Cost	$20,720	
	Prototyping Materials	$10,847	
	Total Engineering Est.	**$31,567**	

Wheels Actuated

Wheel Actuators (Per row unit)		
Component	*Cost*	*Qty*
Brackets, Hardware	$50	1
Gearmotor	$100	2
Driveline (Pulley, gears, e	$80	2
Sensor	$70	2
Cables	$10	4
	Totals	$590

Mechanical Prototype	*Matl's*	*Eng. Hrs*
Understand basic force requirements		3
Specify Motors		3
Design Driveline		8
Build Prototype (1 row unit)	$885	8
Test & Refine Prototype	$500	15
	Total:	$4,345

Electrical Prototype	*Matl's*	*Eng. Hrs*
Specify Sensors		4
Design & Prototype RCU on Bench	$345	28
Design & Prototype OI on Bench	$464	28
Design Enclosures	$60	8
Build Prototype (1 row unit)	$462	20
Test & Refine Prototype	$200	30
	Total:	$10,971

Row Control Unit (RCU)		
Component	*Cost*	*Qty*
Housing	$10	1
Cables	$15	2
Connectors	$4	10
Microcontroller	$30	1
Motor Controller	$60	2
	Totals	$230

Preparation for Production	*Matl's*	*Eng. Hrs*
Build 3 row unit cultivator	$4,038	12
Make Electrical Schematics		16
Make Mechanical Drawings		8
Handoff to Electrical Supplier(s)		20
Write Owner's Manual		20
	Total:	$10,118

Operator Interface (OI)		
Component	*Cost*	*Qty*
LCD Panel	$50	1
Microcontroller	$80	1
Housing	$40	1
Connectors	$4	3
Cables	$15	3
Switches	$1	5
	Totals	$232

Production Costs (Materials only - no assy, etc.)			
Base Cost	$232		
Per-row-unit cost	$820		
# of row units	3	13	25
Total System Cost	**$2,692**	**$10,892**	**$20,732**

Engineering Costs	***Rate***	***$80***	***/hr***
	Total Time	231	hr
	Eng. Labor Cost	$18,480	
	Prototyping Materials	$6,954	
	Total Engineering Est.	**$25,434**	

Wheels Actuated, No Zones

Wheel Actuators (Per row unit)		
Component	*Cost*	*Qty*
Brackets, Hardware	$50	1
Gearmotor	$100	2
Driveline (Pulley, gears, e	$80	2
Sensor	$70	2
Cables	$10	4
	Totals	$590

Row Control Unit (RCU)		
Component	*Cost*	*Qty*
Housing	$10	1
Cables	$15	2
Connectors	$4	10
Microcontroller	$30	1
Motor Controller	$60	2
	Totals	$230

Operator Interface (OI)		
Component	*Cost*	*Qty*
LCD Panel	$50	1
Microcontroller	$80	1
Housing	$40	1
Connectors	$4	3
Cables	$15	3
Switches	$1	2
	Totals	$229

Mechanical Prototype	***Matl's***	***Eng. Hrs***
Understand basic force requirements		3
Specify Motors		3
Design Driveline		8
Build Prototype (1 row unit)	$885	8
Test & Refine Prototype	$500	15
	Total:	$4,345

Electrical Prototype	***Matl's***	***Eng. Hrs***
Specify Sensors		4
Design & Prototype RCU on Bench	$345	25
Design & Prototype OI on Bench	$458	20
Design Enclosures	$60	7
Build Prototype (1 row unit)	$459	18
Test & Refine Prototype	$200	25
	Total:	$9,442

Preparation for Production	***Matl's***	***Eng. Hrs***
Build 3 row unit cultivator	$4,034	12
Make Electrical Schematics		15
Make Mechanical Drawings		8
Handoff to Electrical Supplier(s)		18
Write Owner's Manual		20
	Total:	$9,874

Production Costs (Materials only - no assy, etc.)			
Base Cost	$229		
Per-row-unit cost	$820		
# of row units	3	13	25
Total System Cost	**$2,689**	**$10,889**	**$20,729**

Engineering Costs	***Rate***	***$80***	***/hr***
Total Time		209	hr
Eng. Labor Cost		$16,720	
Prototyping Materials		$6,941	
Total Engineering Est.		**$23,661**	

Wheels Actuated + Hydraulic Switchover

Wheel Actuators (Per row unit)		
Component	*Cost*	*Qty*
Brackets, Hardware	$50	1
Gearmotor	$100	2
Driveline (Pulley, gears, e	$80	2
Sensor	$70	3
Cables	$10	4
	Totals	$660

Mechanical Prototype	*Matl's*	*Eng. Hrs*
Understand basic force requirements		4
Specify Motors		6
Design Driveline		14
Build Prototype (1 row unit)	$1,440	14
Test & Refine Prototype	$800	20
	Total:	$6,880

Swingarm Actuator		
Component	*Cost*	*Qty*
Brackets, Hardware	$50	1
Hydraulic Cylinder	$150	1
Hydraulic Hoses	$100	1
	Totals	$300

Electrical Prototype	*Matl's*	*Eng. Hrs*
Specify Sensors		4
Design & Prototype RCU on Bench	$345	28
Design & Prototype OI on Bench	$464	28
Design Enclosures	$60	8
Build Prototype (1 row unit)	$462	18
Test & Refine Prototype	$200	25
	Total:	$10,411

Row Control Unit (RCU)		
Component	*Cost*	*Qty*
Housing	$10	1
Cables	$15	2
Connectors	$4	10
Microcontroller	$30	1
Motor Controller	$60	2
	Totals	$230

Preparation for Production	*Matl's*	*Eng. Hrs*
Build 3 row unit cultivator	$5,703	12
Make Electrical Schematics		20
Make Mechanical Drawings		8
Handoff to Supplier(s)		25
Write Owner's Manual		20
	Total:	$12,503

Operator Interface (OI)		
Component	*Cost*	*Qty*
LCD Panel	$50	1
Microcontroller	$80	1
Housing	$40	1
Connectors	$4	3
Cables	$15	3
Switches	$1	5
	Totals	$232

Production Costs (Materials only - no assy, etc.)			
Base Cost	$232		
Per-row-unit cost	$1,190		
# of row units	3	13	25
Total System Cost	**$3,802**	**$15,702**	**$29,982**

Engineering Costs	***Rate***	***$80***	***/hr***
	Total Time	254	hr
	Eng. Labor Cost	$20,320	
	Prototyping Materials	$9,474	
	Total Engineering Est.	**$29,794**	