Gearmotor & "Windshield wiper" motors as direct drive units for MIT-E Vent: *"TwinDrive"*
March 28, 2020, updated 3/30/2020
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https://e-vent.mit.edu/

Background

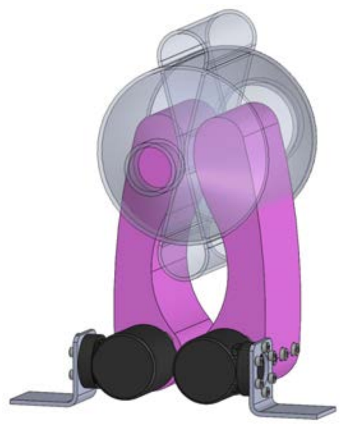
On March 12, 2020 I started the quest for design, build, test an emergency breathing assist device in response to the critical shortage of ventilators the COVID-19 pandemic has created. My lab members volunteered to help and we formed the MIT-E Vent team (https://e-vent.mit.edu/ where we post information to share with the world) and we learned rapidly and made a lot of progress. Hindsight is often 2020, and this being 2020. The full story is part of another document… the purpose of this document is to describe how a geared mechanism led to a direct drive mechanism.

In general, rotary motion is preferred over sliding because it is more robust for millions of cycles in an environment that cannot be relied upon to carefully maintain the unit. Hence two hands pivoting together to squeeze an "Ambu bag" is a natural design to pursue. The force required on a pivoting "hand" at the Ambu bag center is about 100N to generate 50 cm H2O pressure. The distance from the pivot to center axis of a 125 mm (5 inch) diameter bag to get good "squeeze" is about 125-150mm. The speed of the bag center for compression to meet inspiration is thus about 176 mm/sec (7 in/s). FIRST robotics uses gearmotors with integral encoders and indeed an AndyMark PG71 motor we had on-hand proved to be very useful to develop the design concept of using a single motor to drive two pivoting hands geared together. However, millions of units worldwide will be needed, and in the search for a strong gearmotor to pivot the two hands geared together, it was suggested by many people contacted for their thoughts on the design to make it work with windshield wiper motors: Indeed a former student and business partner on ventures past, Dave Gessel who lives in Iraq, emailed me *"There aren't any new "parts" here other than spares for things like cars or maybe washing machines. Car seat or windshield wiper motors, smart phone control, fabrication with hand tools OR import complete."* But windshield wiper motors typically have 10-15 N-m of stall torque, not enough to power two hands…

Meanwhile, a whole series of emails between the MIT E-Vent team and Toyota indicated that their wiper motors could match the specs of the AndyMark gearmotors, and an encoder could then be attached to one of the shafts that holds the hands. I had been discussing different drive methods for "paddle hands" with Richard Moore from Ford who was pursuing a system actuated by a geartrain powered by a standard motor Ford uses in its products. Richard was kind enough to check on windshield wiper gearmotor information (we still need to know what the allowable side load is on the output shaft)…

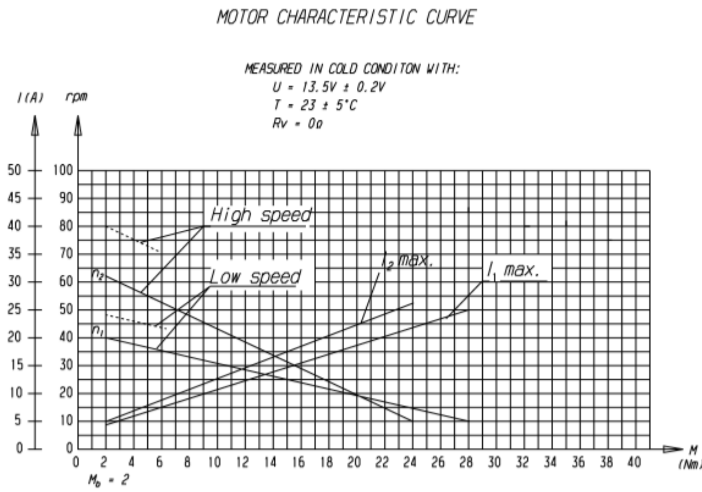
In addition, a few days ago my friend (and alum form my lab at MIT) Dr. Matthew Van Doren, who I had asked to help with stepper motor control for the *TopDrive* system created in concert Marcel Botha from NewLab.com. Steve Cohen and Marcel started NewLab as a way to help start a design and manufacturing renascence in NYC. Marcel and his amazing team of design people in New York in a matter of only a day took my early solid model for a "Top Drive" and evolved, built, and delivered test units for controls development.

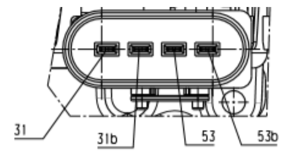
Matt was working on the controls for the *TopDrive* unit provided to him by NewLab, and it got him thinking that modular robotic actuators (HDT A24 Actuator) that his brother's robotics firm developed could directly power the fingers (or hands) that squeeze the Ambu bag. Matt took the shape of the rolling contact hands from the *TopDrive* and created a direct drive image or a very simple and modular system core:



The HDT actuators are self-contained with controller, encoder…. really nice units. Perhaps more expensive than a couple of windshield wiper motors on a bracket with a simple control system, but hundreds a month can be in production right away, and they are a proven hardened and high-performance product, and HDT is an approved FDA manufacturer of such hardware.

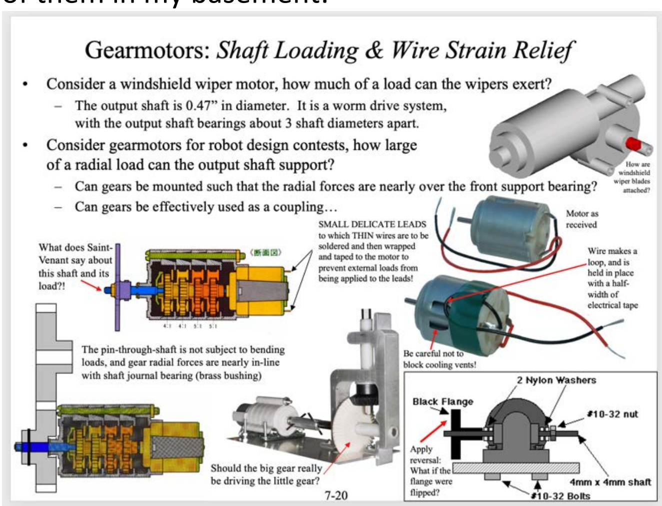
Shortly thereafter, Richard Moore sent me this image of a Ford windshield wiper motor spec sheet, which is 2-3x stronger than what I have been used to in earlier hobby projects, and the higher torques now available inspired me to think fresh:



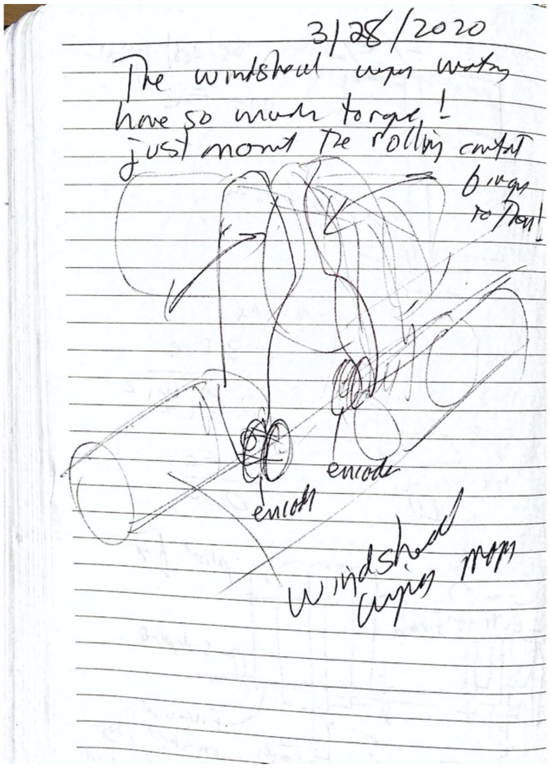


BASIS CHARACTERISTICS	
RATING VOLTAGE	12V
TESTING VOLTAGE	13.5V
BREAKAWAY TORQUE	28Nm (LOW SPEED) 24Nm(HIGH SPEED)
BREAKAWAY CURRENT	25A MAX (LOW SPEED) 27A MAX(HIGH SPEED)
OPERATING SPEED (LOAD:2Nm)	40-48 RPM (LOW SPEED) 62-80 RPM (HIGH SPEED)
OPERATING CURRENT	4A MAX (LOW SPEED) 5A MAX (HIGH SPEED)

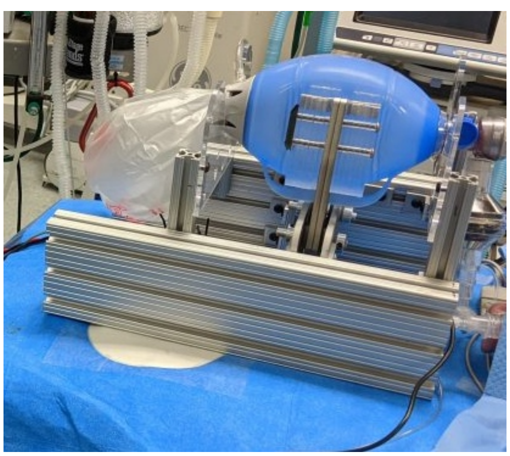
Déjà vu? Below is the image from my book FUNdaMENTALS of design that I wrote for course 2.007 where 25 years ago we were providing students big windshield wiper motors (note image in upper right of page) to use in their kits which had been donated by Ford! I still have a drawer of them in my basement:



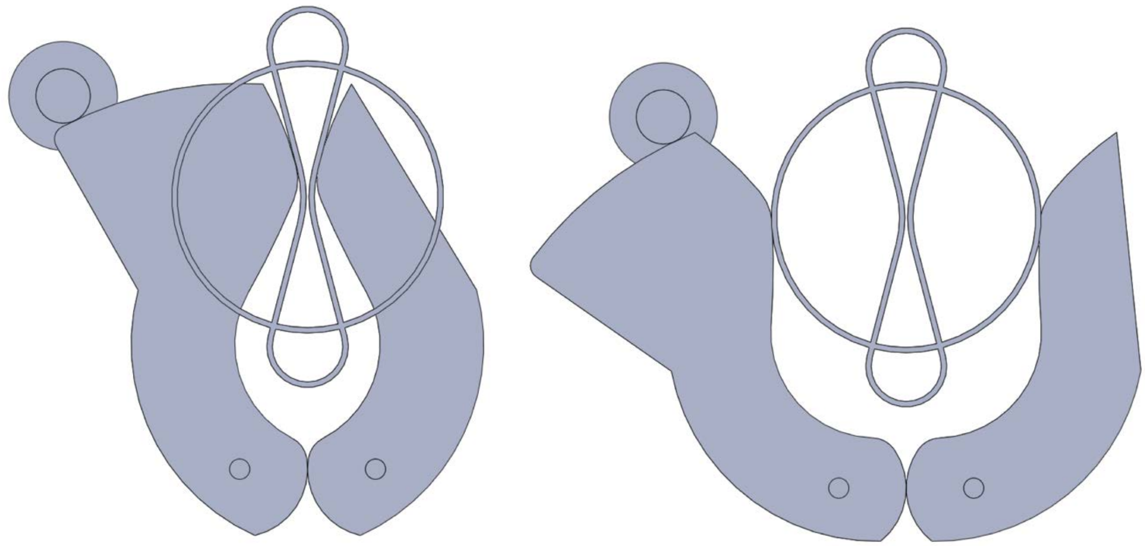
I had to put all this together, so I took a dog walk Saturday afternoon through our 100 acre woods, thinking about all the calculations I had been doing in spreadsheets for the geared hand designs, and the dimensions and forces….. POW it hit me while doing a first order analysis on the trail…. The windshield wiper motors themselves might along work as a direct drive actuator. I came home and sketched the idea and then went to work modifying y design spreadsheet for the geared hands design while Solid Modeling the concept driven by the primary functional requirements of "hands" attached directly to output shaft of gearmotors (minimize complexity), minimize rubbing of the bag and motion of bag centerline while achieving a tidal volume flow of > 800 cm^3, and of course safety and fail safe operation ability.



Had someone suggested this before in the past few days? I do not recall as these past days has been such a whirlwind as every day we hear how things are getting worse… so many lives at stake…. Thus, the thought was we could attach an “arm” to a windshield wiper motor output shaft, where the arm has “fingers” on each side like the MIT-E Vent unit we developed to create a wide “hand” to hold and compress the bag:



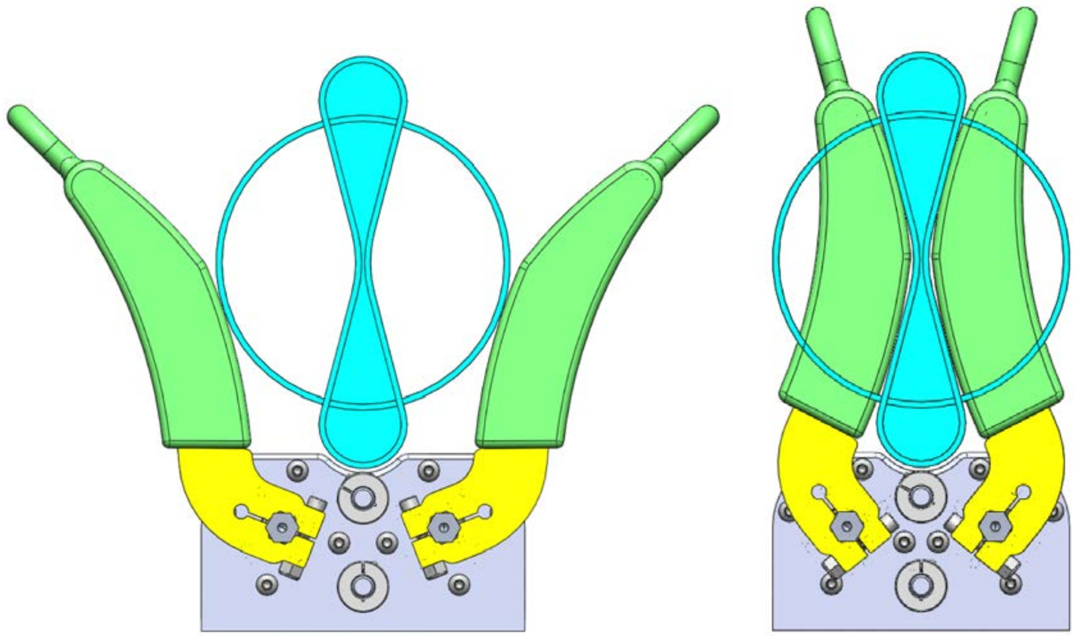
The key is the shape that squeezes the bag nicely as these early images from development of the *TopDrive* design report of 3/21/2020 show:



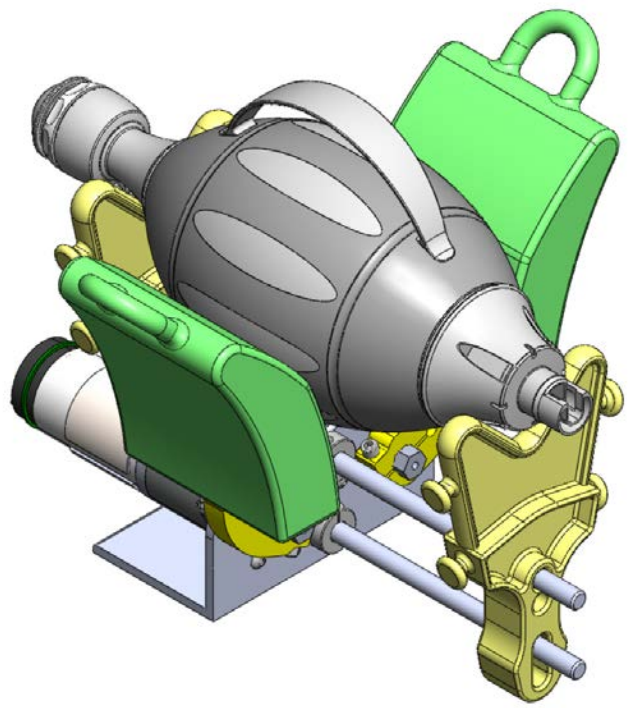
More than just effective rolling contact, then hands need to press on a wide surface region of the bag from both sides to get the “two hands” volme potential of the bag (>800 cc’s tidal volume of air).

***“TwinDrive”* concept**

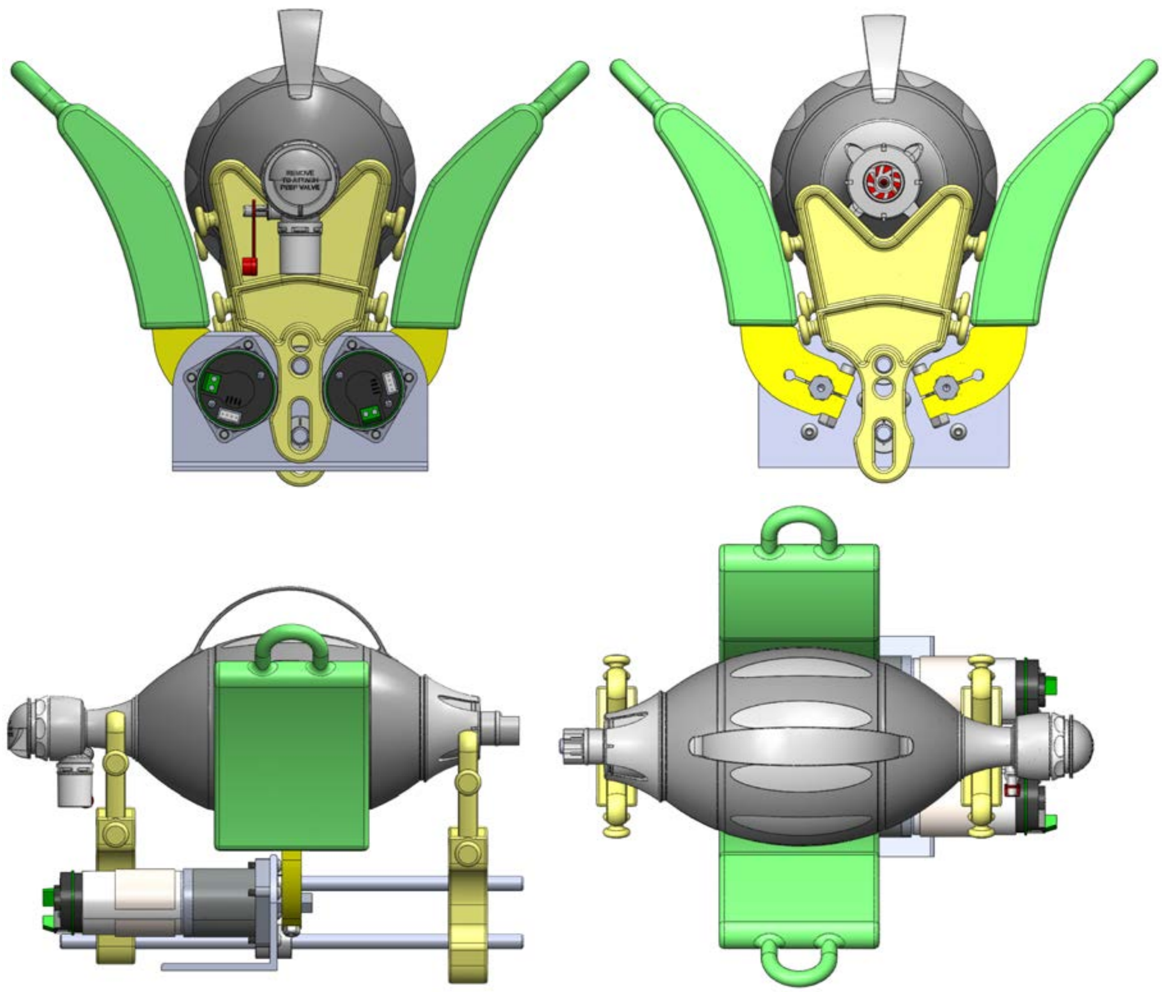
The key to direct drive the hands that squeeze the bag is a gearmotor to whose output shaft can be directly affixed an ”arm” with a “hand” that pushes on the bag. To minimize the torque required is to reduce the distance from the center of the bag to the rotation axis; however, the further away the hand is from the gearmotor axis of rotation, the more linear and uniform the motion of bag squeezing. The challenege then is to create a “cam-like” shape that is nice to the bag (minimize rubbing and motion of bag centerline). The original design was evolved with a few long contemplative walks through the woods to yield a reduction from the original 5.5” to 4.5” which results in 18% reduction in torque. The profile was also evovled to squeeze more of the bag giving more potential tidal volume:



A resulting design of “core engine” for use with gearmotors with integral encoders[1] is:



[1] E.g., https://www.andymark.com/products/hex-pg-series-gearboxes-options?Gear%20Ratio=71%3A1&quantity=1&Motor%20%26%20Encoder%20=Installed&Shaft%20Size=1%2F2%20Hex



One can envision how the core design can be easily adpated for use with diffferent gearmotors or windshield wiper motors which can be mounted on opposing faces of a deep channel.

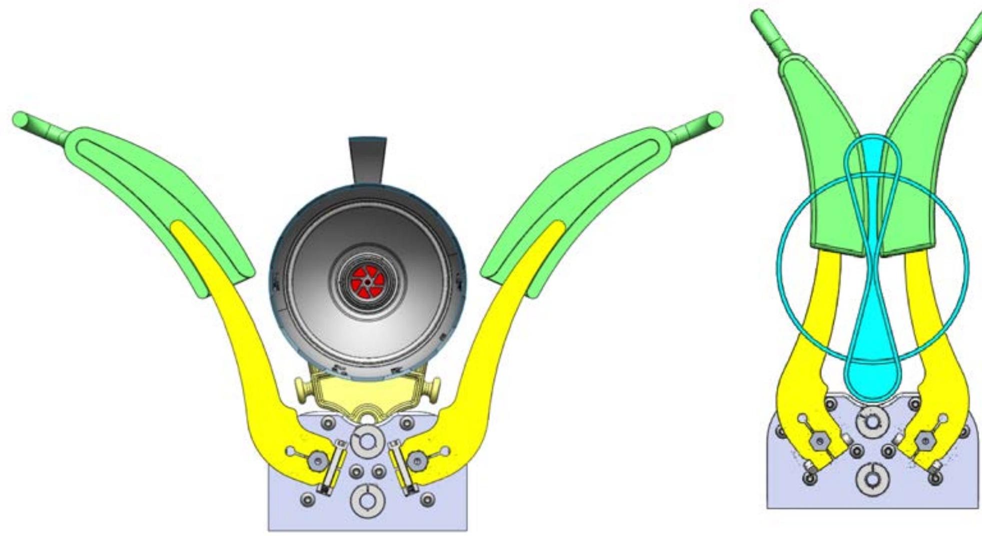
Position Sensing

Gearmotors with encoders provide very good feedback, but they will still need a home position flag. Windshield wiper motors generaly do not have inetrgal position sensors, but if they did (for dorect drive of wier blades) that would be a huge binus.

Else it would be very straightforward to on the arm have an arc shape on the bottom surface with fine “teeth” that an inductive sensor “count” (two can be used to yield quadrature effect)…. The design concept is very straightforward and the accompanying design spreadsheet can help bright engineers and makers all over the world rapidly design and make breating assist devices, whch are cntrolled by systems created by their electrical engineering counterparts, all working othegtehr with medical doctors to help people.

Fail-Safe Design

Some gearmotors with very high ratios or with wormgears are not backdriveable, as is common with many windshield wiper motors. This presents a hazerd of the bag is squeezed and the motor fails, because a clinician could not simply pry open the hands and pull the bag out. The answer is to pull the bag and hands out: this is made possible by creating a smooth curve over which printed hands slide:



“Hands” on 3D printing

3D printing cn be most helpful to prodce the bag fixturing devices (although they can later be injection molded). The “hands” (green) can be mlded with a rotating core, but for now can be 3D printed. They have generous sections, but FEA stress analysis should be done as well as testing because many 3D printing processes produce nice parts but can be mdest strength, and these “hands” need to last for at least one million cycles (ideally 10 million). It isanticipated that creative people will evolve the hands to optimize their strength and minimize materials used while maintaining the bag-contact and emegerncy pull off surfaces.

Overall package

The above represents the “core engine”, where the solid model elements and design spreadsheet will be posted on https://e-vent.mit.edu/. However, it still needs the overall package (can it be run “open” as shown or is some shielding needed? Should it come with a stand? Where does the power electronics and controller and display screen go? … Many details to be done, but this could be done rapidly by skilled product design team, and units could be up and running in less than a week.

Path Forward

1) Maintain full speed ahead on producing the very robust “Top Drive” system being brought forward by NewLab should continue forward full speed as it is ready to go into production as soon as pig trials are completed Monday 3/30/2020.
2) Start rapid deveopment of the DirectDrive system:
    a. Standardize the “arm” and hand designs (or at least te upper curved part of the arm and the hands): ideally the hands should be designed to be molded.
    b. Launch the "high end" direct drive version which is the HDT A24 Actuator based system, which would readily achieve FDA approval as it was developed under a DARPA grant for medical applications as I recall. Dr. Alex Slocum Jr. (MD) and Dr. Albert Kwon have been working on FDA documents for the current gear driven finger designs we have been developing and they could thus work with Dr. Van Doren to move this rapidly forward.
    c. Bring forth the direct drive version with off-the-shelf gearmotors with integral encoders. A generic control system is needed.
    d. Automotive industry and its supply chain quickly configure a windshield wiper motor direct drive version, position sensing can be achieved with the inductor sensor looking at ridges on the “arm” as it rotates.
    e. In all of the above, there is some risk in can for example windshield wiper units really withstand operating continually for 6 months? They might need a fan to cool the motors but that should not be an issue and they would be very inexpensive… the MIT team did this with the AndyMark motors successfully.

Note someone might ask “why did you not think of direct drive first?” Well, the above is recounting the process we have done and in the end the development of the hand shape the controls, the pig tests…. All going forward we likely would not be much faster, and spent maybe a bit less money and have fewer frayed nerves, but in the end wat natters is get emergency breathing assist devices to hospitals ASAP

The spreadsheet calculations for the windshield wiper motor-based system are shown below so they are all in this one document:

MIT-E VENT Direct Drive System Design spreadsheet			
Spreadsheet to investigate ambu bag squeezer using "hands" directly mounted to wobust windshield wiper motors			
created by Prof. Alex Slocum March 28, 2020, see "Revisions" tab			
Inputs in **BLACK**, Outputs in **RED**			
Bag and Hand			
Bag diameter	Dbag	**125**	mm
		5	inches
Bag length effectively compressed	Lbag	**125**	mm
Percent bag diameter compressed for full tidal volume	pbdc	**90%**	
Distance "hand" moves towards center of bag	disphand	**56**	mm
distance plane of center of bag to center of hand rotation	R_1	**114.3**	mm
		4.5	inch
arc of travel of hand to compress bag	arcfing	**28**	degrees
Respiration			
Peak for shorter periods	resprate	**40**	breaths per minute
Average for mechanism life and motor power calculations	resprateavg	**30**	breaths per minute
seconds per breath	spb	**2.00**	
Inspiratory/expiratory ratio	ier	**1:4**	
Inspiration ratio	insp	**1**	portion of cycle
Expiration ratio	expr	**4**	portion of cycle
Total parts	tpb	**5**	total portions
Time to inhale	tinsp	**0.40**	seconds
Time to exhale	texh	**1.60**	seconds
Portion of inhalation to ramp	pcr	**0.1**	percentage
time to ramp to pressure and ramp down	trtp	**0.04**	seconds
Percent of inhale time for ramp up and ramp down	xpramp	**10%**	
average linear speed of hand at bag center	vhandc	**176**	mm/sec
average rpm of finger	rpmfing	**14.69**	rpm
Forces on "Hands" from airway pressure in bag			
peak airway pressure	pap	**40**	mmHg
		52	cmH2O
factor higher to force from bag through circuit	papeta	**0.9**	
bag pressure	pbagmm	**44.4**	mmHg
		0.058	atm
		0.860	psi
		0.006	N/mm^2
	cmH2O	**57.8**	cmH2O
	Areabag	**15625**	mm^2
Radial force on bag from each hand	Fbag	**92.6**	N
		20.8	lbs

Estimated Motor Size Required for the System			
Life cycle			
Breaths per day	bpdavg	**43,200**	
Days of life of machine before rebuild	dolm	**180**	
Total machine cycles required	tmcd	**7,776,000**	cycles
Motor Power estimate to start design			
Radial velocity of bag sides during inhalation	Vrbagsides	**156.3**	mm/sec
Power applied to compress bag during inhalation portion of breathing cycle	Pbaginhale	**29.0**	Watts
mechanical system effieicny (gearmotor and connection to bag mechanism)	etamech	**0.8**	
Oversize motor for 100% duty cycle	ovszf	**150%**	
Estimated total peak motor mechanical power to select candidate motors	Pmotorest	**54**	Watts
Direct Drive Design: One windshield wiper motor per hand			
Force on a each "hand" as bag is compressed	Ffinger	**92.6**	N
gearbox output torque needed	Tgm	**10,590**	N-mm
		94	lb-in
Motor Selection and operating parameters			
N motor size (Nema 23, 34 or Gearmotor 1, 2, 3 see workbook "Motor Options"	Nmsize	**3**	
Stall torque	Tstallsm	**28.0**	N-m
	Tstallsmm	**28,000**	N-mm
Free speed	wfree34	**70**	rpm
max radial force 20mm from face	Fradmaxm	**200**	N
required speed for respiration cycle	rsarc	**15**	rpm
torque available at required speed	NemaTas	**22,126**	N-mm
torque required for desired performance	tgm	**10,590**	N-mm
		94	lb-in
Summary			
Airway pressure provided (as requested)	pap	**52**	cmH2O
Airway pressure possible if all torque aailable at speed is used	papmax	**109**	cmH2O
Peak Inspiratory Pressure valve threshold		**75**	cmH2O