AC 2012-4978: HUMAN-POWERED ENERGY-EFFICIENT VEHICLE DESIGN

Dr. Alamgir A. Choudhury, Western Michigan University

Alamgir A. Choudhury is an Associate Professor of industrial and manufacturing engineering at Western Michigan University, Kalamazoo, Mich. He earned a B.S. in mechanical engineering from BUET (Dhaka), and M.S. and Ph.D. degrees from NMSU (Las Cruces). His interest includes computer applications in curriculum, mechanics, MCAE, instrumentation and control, and fluid power. He is also a registered Professional Engineer in the state of Ohio and affiliated with ASME, ASEE, SME, and TAP.

Dr. Jorge Rodriguez P.E., Western Michigan University
Mr. Jian Peng He, Western Michigan University

Jian (Ben) He will have earned a bachelor's of science degree in graphics and design technology at the Western Michigan University by 2012. He is currently serving as a vice president Tau Alpha Pi, an engineering honors society. He is also working part time as a Fire Extinguisher Assistant, a fire equipment restoration job to which he thoroughly enjoys. He has been a distinguished student in the WMU Physics and Engineering Design Technology Department as an elected physics student of the semester in 2010 and an outstanding student in 2012. In the late 1999, he immigrated to the United States for better education, and has always appreciated his parents and sister ever since. He embraces free-thinking philosophy and astronomy.

Ryan Kamm
Saleem Hason Hinton
Mr. Brandon De Young

Human powered energy efficient vehicle design

Abstract

Recent awareness in energy consumption and environment has generated interest in eco-friendly transportation system in both developed and developing regions of the world. Government and private sectors are encouraging innovative development and use of energy efficient vehicles for transportation of people and goods. Design and development of such systems is a popular design issue in both academia and industry. In this paper, an industry sponsored student project for design and development of a human powered transportation system is presented. It allows a single rider to move in all types of terrain by transferring power to the drive train through the use of a biodegradable hydraulic fluid. Besides the design criteria specified by the project sponsor, functionality, safety and reliability, manufacturability, and cost effectiveness are focus of this design process. Overall design objective is to minimize the weight and maximize energy efficiency of the low power hydraulic drive train. Among the innovative human powered transportation ideas, an upright carbon fiber configuration is adapted. It optimizes rider comfort, weight and provides support of all hydraulic components and drive train. The pedal power of the rider runs a fixed displacement axial piston pump and transfers the pressurized fluid to a hydraulic motor of similar classification driving the rear wheel. A pressure sensing hydraulic circuit allows storage of the pressurized fluid in a hydraulic accumulator and releases the fluid on demand such as during the uphill motion. A light weight mechanical drive train provides appropriate torque to drive the pump and driving wheel under all driving conditions. In the spring of 2012 the system will participate in a national design competition among twelve engineering schools. The designs will be evaluated based on established design criteria and performance of the system in a 200 m sprint, 10.8 mile endurance, and an energy recovery efficiency race.

1. Introduction

History of human powered transportation goes back as far as 3500 BC when wheels were used to pull carts in ancient civilizations. Advent of steam engine and internal combustion engine in the 17th century propelled development of modern transportation system on the wheels. Availability of inexpensive source of energy gave rise to mass transportation system in the following centuries. In recent years, rise of energy cost, awareness on depleting fossil fuel reserve, and concern for environment has generated awareness in developing more eco-friendly and sustainable technology in transportation across the globe. Currently there are more than 800 million cars and truck on the road worldwide, burning in excess of 260 billion gallons of fuel each year releasing over 5 trillion pounds of CO_2 in the atmosphere [1]. Due to accelerated economic growth in the developing regions of the world, these numbers are increasing rapidly. Concern for environmental pollution and global warming underscores the need to stop or reverse this trend through more efficient and eco-friendly transportation system in the near future.

Though human powered transportation is no match for load capacity, speed, comfort and convenience of current mechanized transportation system, there is renewed interest in human powered transportation. Besides cost, environmental and health benefit, worldwide, bicycle will remain as a popular mode of transportation for indefinite future. Currently, worldwide there are 1.7 Billion bicycles and additional 100 million bicycles are being produced each year. There are wide varieties of designs and configuration of bicycles to meet people's riding need. Vast majority of these bikes are chain driven upright type of design. For pleasure ride people use recumbent, tandem and other exotic configurations. In many developing regions of the world, three or four wheeled designs are commonly used for transporting people and goods. Bicycle is the most energy efficient mode of traveling, requiring the least amount of energy per person per unit distance [2]. Though standard bicycle is a very energy thrifty device, it is not able to harvest the kinetic energy lost in process of braking or slowing down. Capturing and storing this kinetic energy for later use would vastly enhance the utility of bike as a pleasure vehicle as well as a transportation system. But standard bicycles are not able to capture the kinetic energy lost during braking to utilize it as necessary such as during climbing uphill terrain.

Development of sustainable energy efficient human powered vehicle is a complex task and will be of research interest in academia and industry for foreseeable future. In 2006, MIT Vehicle Design Summit [3] brought 60 engineering students from 13 countries together in a collaborative effort to design, build and test alternative transportation technologies and prototype commuter vehicles. Using a bicycle pedal driven mechanism, a system was designed as an electric hybrid of Assisted Human Powered Vehicle. In 2006, Human Powered Vehicle Challenge [4] sponsored by the American Society of Mechanical Engineers provided a frame work for senior design projects where students designed a variety of system including single and multiple rider vehicles. These were designed as chain driven bicycle mechanism along with wind shield to minimize aerodynamic drag.

The system presented in this paper is part of standard two semester capstone design project involving design of a product or process, analysis, simulation, prototype, fabrication, assembly, testing and assessment of design. Students are required to utilize current technical tools to solve the chosen problem. Results of such projects are presented as written report, and public presentation of the overall project. They also use project management tools to plan and track project progress. Typically in the two semester project, students complete the design and analysis of the subject in first semester, and fabrication and development of the prototype or actual system during the second semester. Recognizing the value for student practices in responding to real-world needs, expectations, and constraints, more and more corporate sponsorship and involvement are sought in these projects. Therefore, design and development of energy efficient transportation system with industry sponsorship is a very coveted topic for senior design projects. Besides gaining awareness in energy efficiency and sustainability, experience in such project prepares program graduates seek employment in this growing field. In this project, an interdisciplinary group of four students (three in Manufacturing Engineering Technology and one in Engineering Design Technology) from the department of Industrial and Manufacturing Engineering (IME) of Western Michigan University (WMU) designed and developed the system in two semesters.

To promote hydraulics education and development of new technology in energy efficient motion control and vehicle design, Parker Hannifin Corporation collaborates with a group of universities across the nation. They helped to incorporate fluid power practices in engineering and engineering technology curriculum and establish laboratories in these universities. Since 2004, Parker is sponsoring a hydraulic bicycle design competition among those universities. The purpose of the competition was to challenge undergraduate engineering and engineering technology students for innovative design and development of a bicycle that would transfer a rider's manual power to the driving wheel through a hydraulic media without using any chain or direct drive mechanism. In a one year time frame, students of engineering and engineering technology programs of participating universities complete the design and development of the system. In the summer, each university team would meet in Cleveland, OH, for a design competition. Parker provided monetary and material grant to each university to offset the cost of design and fabrication of the system. Parker would evaluate each team based on novelty in design, reliability and safety, manufacturability, marketability, cost, workmanship, and design report. Each team would enter in a 200 yard circuit races and a 10.8 mile endurance race in a hilly terrain. A composite score including all areas of design and performance in the races would be used to determine the overall winner and ranking of individual teams. During the academic year 2011-12, the scope of the competition is broadened to design a Human Assisted Green Energy Vehicle and additional design and performance criteria were established. Beyond twelve universities in the group, three additional universities have joined the competition and the venue of competition has moved to Irvine, CA. In this new competition, student team starts design process at the beginning of Fall semester and completes the project in the Spring semester. The design competition is held at the end of Spring semester.

2. Design objective

The overall objective is to design a human powered vehicle that would utilize a biodegradable hydraulic fluid to transfer rider's power to the driving wheel. The criteria of the design, performance of the vehicle and project time line are specified by the sponsor. Specific objectives of the design are:

- Able to transport a single rider using only manual power
- Transfer and store energy through a biodegradable hydraulic fluid
- Achieve maximum operational efficiency of the pump and motor
- Minimize overall weight of the system
- Meet all specified safety requirements
- Meet specified project time line

At the end the designed vehicle would participate in a competition comprised of 200 meter sprint race, 10.8 mile time trial, and efficiency trial. The purpose of the sprint race is to judge the capability of the system to accelerate and achieve the top speed. In the 10.8 mile time trial, the system will demonstrate its ability to coast along a course and meet the various requirement of the course. Efficiency trial will be used to assess energy storage and delivery capacity of the system. Besides performance in the competition, each design would be judged for

- Ingenuity & Novelty

- Reliability & Safety
- Manufacturability
- Marketability
- Workmanship
- Cost

3. Design process

WMU participated in all previous hydraulic bicycle design competitions. The design team field tested the performance of previous hydraulic bicycles and identified the areas of improvement as (a) reduction of weight both frame and components, (b) efficiency of the hydraulic drive system, (c) ergonomics of the system and (d) drive train performance.

Though Parker provided some material and monetary support, considering their design criteria and project time span, it was decided that development of such a system based on standard design practices would be unrealistic. Therefore, a hybrid design process was established, where no major components would be designed; instead, existing components available in the market would be adapted. Overall design process is shown in Figure 1. The focus was to meet the design criteria, minimize weight, and maximize energy efficiency of the drive system. To achieve this goal, a hydraulic circuit was designed that would allow the rider to switch from cruising mode to charging the accumulator, capturing the kinetic energy while decelerating, or releasing the accumulator energy to assist forward motion by operating a single direction control valve.

For the drive system, two different types of piston pumps and motors with 93% efficiency at their normal operational conditions were selected. But in this system rpm will vary between 0-600 rpm depending on riding conditions. Therefore, it was necessary to map efficiency of these pumps and motors in the 0 to 600 rpm range and the most efficient pump and motor combination would be finally chosen for the system.

Frame: Students studied features of past hydraulic bicycle designs and their performance data. Considering the established design criteria and all areas of judgment, concepts were developed for overall configuration of the system. These concepts were listed in a scale of 0-5 along with a weighting factor for each criterion in a Pugh matrix. The configuration with the highest score (Table I) was an upright aluminum frame with carbon fiber fork weighing 700 grams (Figure 1).

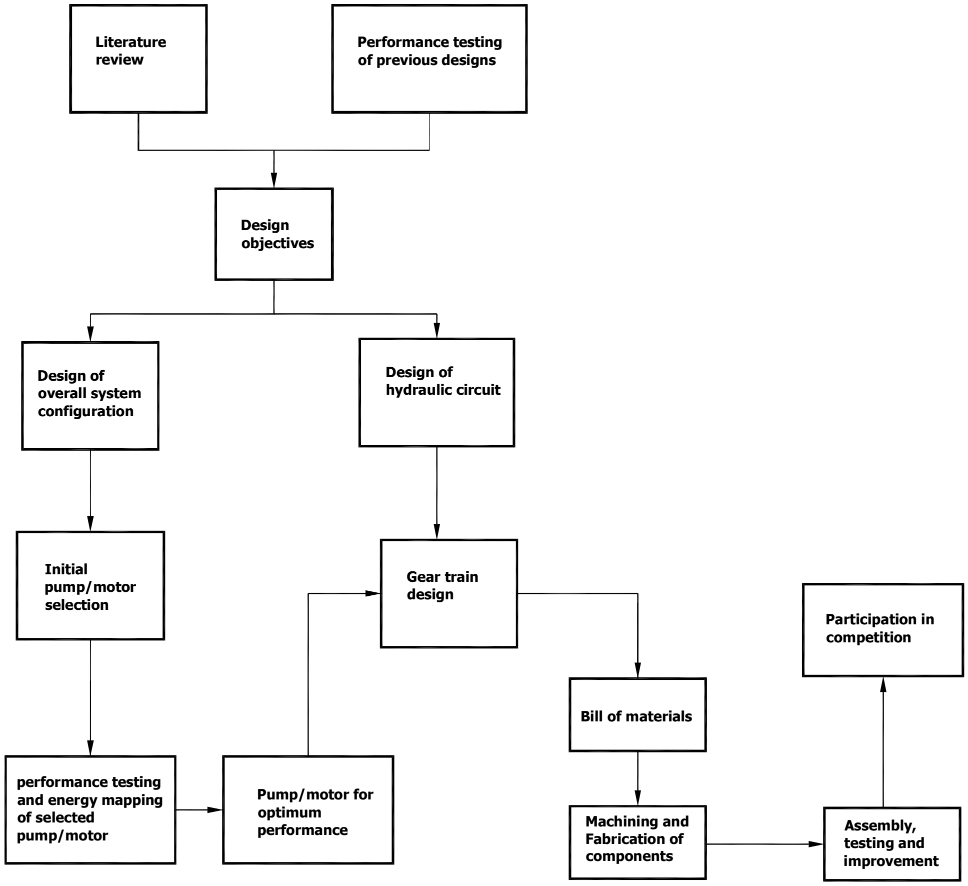

Figure 1
Design process flow chart

Criteria	Wt.	AVG Upright	AVG Rec.	Score Upright	Score Recumbent
Speed (sprint)	10	8.5	5.75	85	57.5
Endurance Race	11	7.5	7.25	82.5	79.75
Eff. Race	12	7.75	7	93	84
Reliab/Safety	14	7	8	98	112
Innovation	9	5.25	7.5	47.25	67.5
Manuf	7	6.75	8	47.25	56
Cost	6	8	5.5	48	33
Market	8	8.5	6.25	68	50
Hills	1	3.5	9.25	3.5	9.25
Turning	3	9.25	3	27.75	9
Comfort	2	6.75	7.75	13.5	15.5
Biomech. Advant	5	8.25	4.5	41.25	22.5
Aerodynamics	4	4.5	8.5	18	34
Weight	13	6.75	6.25	87.75	81.25
Energy Recovery					
				760.75	**711.25**
competition					
Speed (sprint)	10	8.5	5.75	85	57.5
Endurance Race	11	7.5	7.25	82.5	79.75
Eff. Race	12	7.75	7	93	84
Reliab/Safety	13	7	8	91	104
Innovation	9	5.25	7.5	47.25	67.5
Manuf	7	6.75	8	47.25	56
Cost	6	8	5.5	48	33
Market	8	8.5	6.25	68	50
				562	531.75
				1322.75	**1243**

Table I
Pugh matrix for system configuration

Figure 2
Upright configuration of vehicle

Based on the component mounting and rider weight, stress and deformation of the frame was analyzed (Figure 3 and 4) using PTC Pro/Mechanica. The design was modified to withstand the load under several riding scenario.

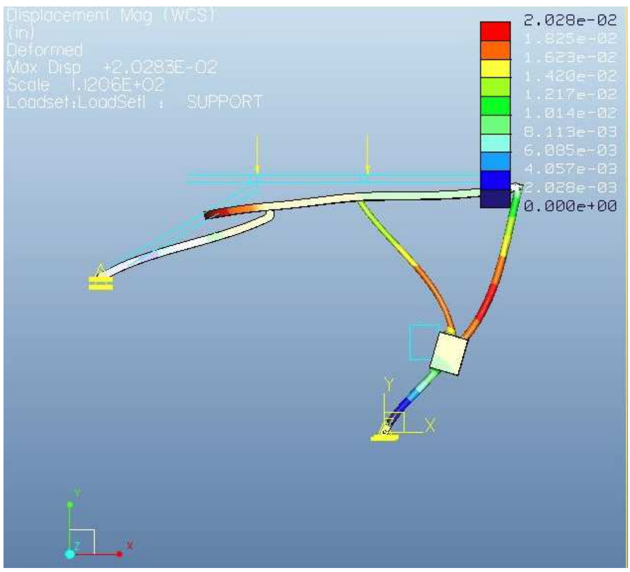

Figure 3
Deformation analysis of accumulator bracket

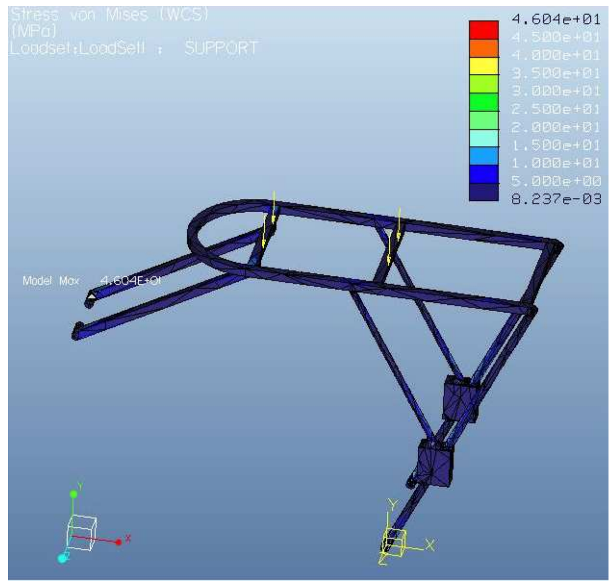

Figure 4
Stress analysis of bracket

Hydraulic circuit: Different types of hydraulic circuits were considered for most efficient performance of the system. Since the main function of the hydraulic system is to transfer of rider's manual power to the driving wheel, most simple hydraulic system would provide maximum efficiency. But the system is also required to perform additional energy capturing, storage and delivery function. Overall functions of the system are:

(a) Coasting for normal riding – pump driven by pedal supplies fluid energy directly to the hydraulic motor that actuates the driving wheel.

(b) Charging accumulator – as the vehicle reaches its top speed, rider can continue pumping fluid to the accumulator and store the fluid energy to be used later as necessary.

(c) Capture kinetic energy – whenever the rider need to decelerate, kinetic energy of system is captured by transforming the hydraulic motor to a pump and storing the fluid power in the accumulator.

(d) Releasing stored energy – whenever a rider needs excess energy to climb a slope, fluid energy stored in the accumulator is released and assists upward motion of the vehicle.

Required flow conditions to achieve these functions are shown in Figure 5. Using three different two position three way direction control valve, these flow conditions will be implemented by the rider.

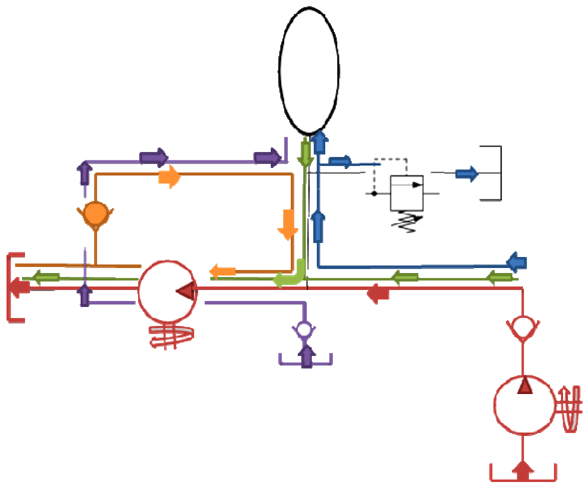

Figure 5
Hydraulic circuit for flow conditions

Energy efficiency mapping: The most critical feature of this design project was to ensure optimal function of the hydraulic power system. Design of all components within the time frame of the project and their fabrication using available manufacturing methods in a typical university laboratory was deemed unrealistic. Instead, it would be more prudent to identify most efficient pumps and motors available in the market and adapt them in design of the overall system.
Most hydraulic motors and pumps for industrial use operate at a relatively high rpm and pressure, and transfer large amount of power. In the human powered hydraulic bicycle, power delivered by the rider is generally less than half HP and pedal rpm vary from 0 to under 100. Similarly the hydraulic motor powered by this flow actuates the driving wheel at a relatively low rpm. In a competitive human powered vehicle, efficiency of hydraulic motor and pump is a critical in minimizing energy loss in the overall power train. Therefore, one needs to ensure that the pump and motor used in such a hydraulic system operate at maximum possible efficiency. In this design process, selection of pumps and motors were based on their efficiency at the operating conditions of the hydraulic system. Manufacturers of pumps and motors provide

operating characteristics of each model at their normal range of operating conditions, which are generally quite high in power, torque and rpm. No commercial light weight hydraulic pumps/motors were available to meet the low power, torque and rpm conditions encountered in a bike. Therefore, it was necessary to test characteristics of pumps and motors which met the required performance criteria at the most. Efficiency information of these components at this pressure and rpm is not present in manufacture’s product data. Therefore, a special test stand is used to map overall efficiency of each pump/motor combination in a hydraulic system. Figure 6 shows the instrumentation for performance measurement of a hydraulic pump driven by an electric motor. Pump rpm, power is manipulated by using electric motor control system. Appropriated pressure is maintained by using a pressure relief valve and the flow control mechanism.

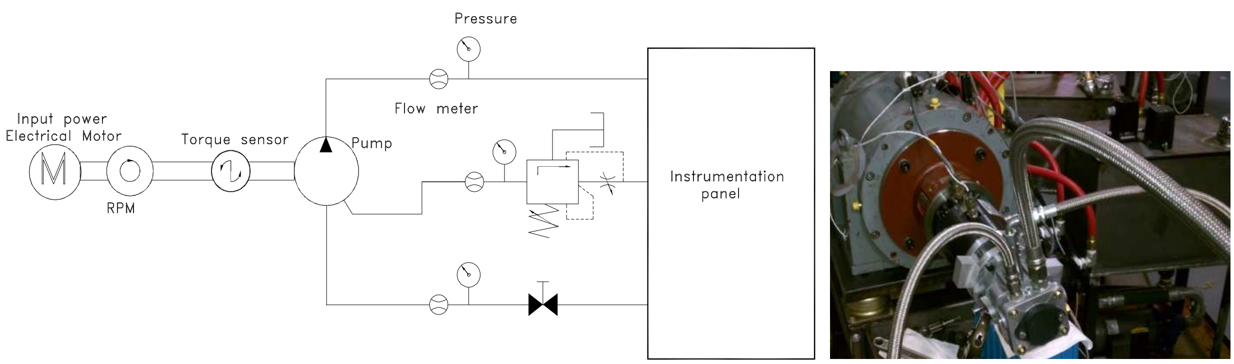

Figure 6

Instrumentation for efficiency mapping of a pump

Two sets of axial piston type pumps and motors deemed suitable for the project were tested at this stage. In both the cases, efficiency improved with increase in rpm. Some of the efficiency characteristics of a pump are shown in figure 7. Models of pump and motor showing highest efficiency were chosen for the design. The operating pressure and rpm of the pump and motor is the desired pressure and rpm of the system.

Drive train: To ensure maximum efficiency of the pump and motor, a gear train is designed to operate the pump and motor at their optimum efficiency. In the pump end, a fixed gear ratio of 1:9 is chosen to increase the pump rpm. In the rear, a six speed internal hub and a fixed spur gear set is used to vary the driving wheel rpm based on driving conditions. For initial travel, rpm of the wheel is minimized and torque maximized. But at high speed cruising, highest gear ratio is selected for maximum rpm and minimum torque. After frame, pump, motor and accumulator selection, required bracket and mounting necessary for anchoring the components in the frame was designed. A bill of materials is generated and the nonstandard components were fabricated.

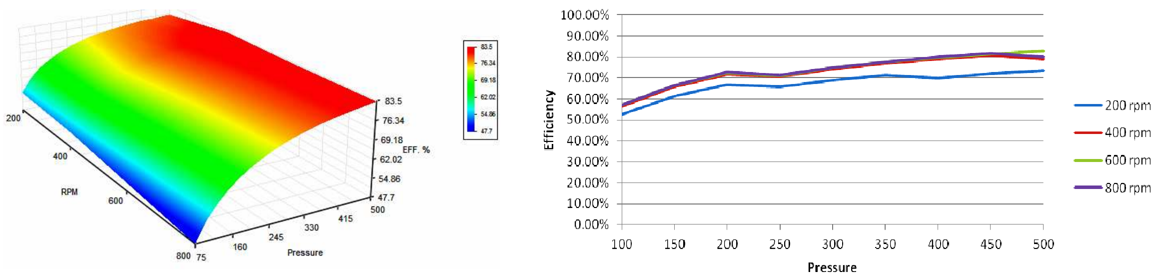

Figure 7

Efficiency mapping of axial piston pump

Assembly and testing: A 2.5 gallon piston type aluminum accumulator and a 3.5 gallon prismatic reservoir were selected for the hydraulic system. Hydraulic valves and gears were machined to minimize their weight. Overall system was assembled and tested for its performance. The design is currently fine tuned based on the test result and prepared to participate in the competition in April 2012.

4. Conclusion:

A human powered hydraulic transportation system is designed to move a single person in most energy efficient manner. A test system is utilized to ensure optimum performance of all major components. The kinetic energy lost during down hill motion is captured, stored in a hydraulic accumulator and later utilized to assist uphill motion. The system is planned to participate in a design competition among fourteen other universities in April.

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