Developing a Motorized Wheel and Low-Cost Pressure Sensor to Improve Ugandan Wheel Cart Transportation and Pricing

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***Abstract*—Currently, Ugandan refugees at the Imvepi Camp transport goods by manually pushing locally developed metal wheel carts. User assessments reveal that pushing wheel carts, especially with heavy loads over long distances and rough terrains, is extremely physically demanding. Additionally, wheel cart pushers that provide their services to customers would greatly benefit from improved methods for weighing loads to assist with accurate pricing. Motorizing the carts and incorporating a weighing mechanism would not only reduce the physical strain of transporting goods, but also empower Ugandan refugees to use the carts more effectively for business purposes. Collaborating with local community stakeholders, our team designed a wheel cart prototype featuring two additions: (1) a streamlined motorized wheel extension to ease pushing and (2) a cost-effective textile-based pressure sensing system for weighing goods. The team will travel to Uganda to demonstrate the solution, integrate it with a locally used wheel cart, and carry out a user evaluation to gather observations and feedback on the design.**

***Index Terms*—**

I. Introduction

Established in February 2017 in Uganda's Terego District, the Imvepi Refugee Settlement was created to accommodate South Sudanese asylum seekers fleeing conflict in their homeland after the nearby Palorinya refugee settlement reached capacity. The settlement houses thousands of refugees and has developed substantial infrastructure, including multiple primary schools, two secondary schools with over 5,800 combined students, and several early childhood development centers. Healthcare is provided through facilities like the Imvepi Health Center II and Yinga Health Centre III, while water and sanitation services have been implemented, with UNICEF reporting that 70% of refugees have access to latrines.

The settlement benefits from its strategic proximity to Arua, a major commercial center in Uganda's northern region that serves as an important base for non-governmental organizations working in the West Nile sub-region. Arua's position as a hub for organizations serving both South Sudan and northeastern Democratic Republic of the Congo makes it a vital support center for settlements like Imvepi. With Arua's population of over 72,000 and its role as a regional transport nexus with regular connections to major cities like Kampala and Gulu, the city provides critical economic and logistical support to the refugee settlement's operations and development.

Transportation within the settlement presents a significant challenge for residents, who currently rely on manually-operated metal wheel carts to move goods across the camp's terrain, shown in Figure 1. These carts, while functional, place considerable physical strain on operators, particularly when carrying heavy loads over long distances and rough terrain. The situation is particularly relevant for cart operators who provide transportation services to other residents, as they lack efficient means to weigh loads for accurate pricing. This transportation challenge intersects with other infrastructure issues in the camp, such as the reported long walking distances to access educational facilities and water sources, especially during dry spells.

Fig. 1. Original wheelcart constructed in Uganda.

II. Stakeholder Assessment

A. Stakeholder Groups

Stakeholders in the wheel cart transportation system can be categorized into three main groups: direct users, service providers, and supporting organizations. Direct users include refugee families transporting personal goods, small business owners moving inventory, and individuals carrying water or supplies over long distances within the settlement. Cart operators who provide transportation services represent a distinct stakeholder group with more specialized needs, as they rely on the carts for their livelihood and require features that support

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business operations, such as accurate weight measurements for fair pricing. Supporting stakeholders include NGOs based in Arua that facilitate settlement operations, creative capacity builders and their teams who build and maintain carts, and settlement administrators who oversee transportation infrastructure.

The needs and impacts vary significantly across these stakeholder groups. For refugee families and individual users, the primary concerns are accessibility, ease of use, and reduced physical strain when transporting essential goods. Cart operators prioritize durability, load capacity, and business-enabling features that allow them to provide reliable services while maintaining sustainable income levels. Supporting organizations focus on the broader implications of transportation efficiency for settlement operations, including how improved mobility could affect access to education, healthcare, and water resources.

B. Customer Journey Map

A customer journey map allows users to document their experience using product from start to finish. It helps designers visualize and identify key moments in the user's journey, enabling them to tailor the design to user needs. We gathered customer journey maps from four Ugandan wheel cart users and compiled their responses in Table I. The stages of the journey include: 1) finding a customer, 2) loading items into the cart, 3) pushing the cart to the destination, and 4) offloading the items. Users indicated whether they felt a) happy, b) fine, or c) unhappy during each stage, while also providing details about their experiences and aspects that could be improved.

The customer journey maps revealed that users are frustrated by the significant effort required to load and push heavy items over rough terrain. We aim to address the challenge of pushing carts, as this involves long durations and distances. Specifically, we ask: how can we design a modular motorized addition that helps move the cart, reducing the energy users must exert and meeting their desire for a more efficient solution?

Additionally, the customer journey maps highlighted dissatisfaction with finding customers for wheel cart services. A key part of using the carts for business involves pricing services based on the load's weight. However, current pricing methods are inconsistent and often fail to scale accurately with weight. To improve the process of securing business and interacting with potential customers, we ask: how can we design a simple, accurate weighing system that allows wheel cart pushers to easily weigh goods for transport and integrate this into their pricing model?

C. Design Constraints

Resource constraints at Imvepi appear to manifest in both technical and economic dimensions. From a technical perspective, the current reliance on manually-operated metal carts suggests limited access to more advanced transportation technologies, possibly due to constraints in local manufacturing capabilities, maintenance infrastructure, and technical expertise. The proposed motorization and sensing systems must be designed within these technical limitations, considering factors such as the availability of spare parts, local repair capabilities, and the durability requirements of rough terrain and frequent use. Additionally, any electrical components would need to account for potential power supply limitations within the settlement.

TABLE I
AGGREGATED CUSTOMER JOURNEY MAP RESPONSES

Stages of Journey		Finding customer	Loading	Pushing	Offloading
Activities		Looking for customers in the market	Putting the goods into the wheel cart	Pushing the wheel cart to the customer's destination	Remove the goods from the wheel cart
Feelings	Happy				X X
	Fine		X X	X X X	X
	Unhappy	X X X X	X X	X	X
Experiences		• It is difficult to find customers who need to transport goods • Inconsistent pricing system	• It takes a lot of energy to lift items into cart • It takes time and experience to load	• Simple to push • It take a lot of energy to push heavy objects in the cart • It can be challenging to push over rough terrain	• Takes less energy to offload • Can take a long time
Customer Wants		Find customers quickly and easily	Load quickly with less energy	Use less energy for pushing	Offload quickly

Economic constraints likely influence both the initial implementation and long-term sustainability of cart improvements. The settlement's reliance on NGO support and the business model of cart operators suggest limited financial resources for significant technological investments. Any enhancements to the cart system must balance increased functionality with cost-effectiveness, considering both the initial investment required from operators or supporting organizations and the ongoing operational costs. The proximity to Arua's commercial center could potentially provide some economic advantages through access to materials and maintenance services, but the overall resource limitations of a refugee settlement context remain a significant consideration.

III. APPROACH

A. Wheel Cart Prototyping

The MIT-based team initially developed a local prototype of the cart to facilitate testing of new designs and features. The Uganda-based team provided approximate cart dimensions, depicted in Figure 2.

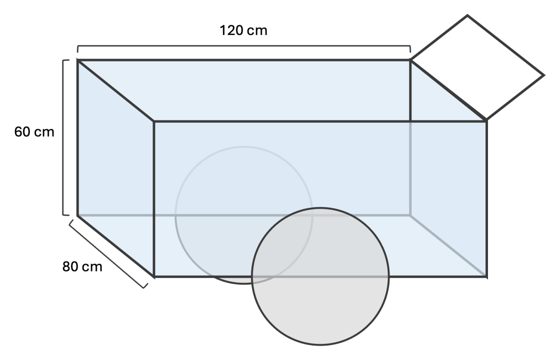

Fig. 2. Approximate wheel cart dimensions.

To construct the prototype, we used the following materials, reasonably matching the original Ugandan wheel cart:

- Metal tubes:
  - Frame: 120cm (x4), 80cm (x4), 60cm (x4)
  - Wheel mount: 75cm (x2), 17cm, (x4)
- Plywood for cart bottom: 120cm x 80cm
- Bicycle wheels: 64cm diameter (x2)
- Metal axle (x2)

Fig. 3. The MIT team welding the wheel cart frame.

To assemble the wheel cart, we used metal inert gas (MIG) welding machinery, a metal cutter, metal grinder, a jigsaw, and a drill. The steps for building the wheel cart prototype include:

1) Cut metal tubes to the indicated sizes and quantities.
2) Drill holes through the center of the 2 120cm frame tubes and the 2 75cm wheel mount metal tubes.
3) Weld the metal frame, then the wheel mounts. Weld the wheel mounts onto the frame. Grind the welded joints for a smooth finish.
4) Attach bicycle wheels to mount using the axle through the pre-drilled holes.
5) Cut a piece of plywood to the indicated size and place it on the bottom of the cart.

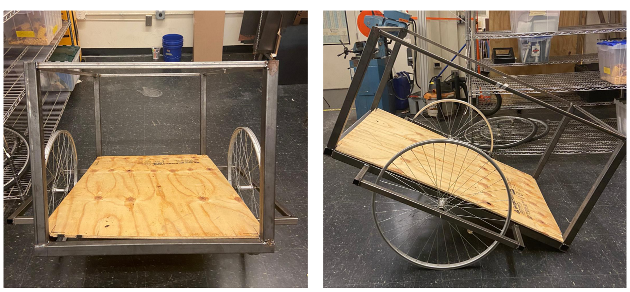

Fig. 4. Initial MIT-based wheel cart prototype.

B. Motorized Wheel

Modular motorization has significant potential to ease some of the physical labor needed to push current wheel carts. This could allow trips to be completed faster, leading to higher capacity for using the carts as a means to support local entrepreneurship.

Inspired by hobbyist electronics in which non-motorized elements such as scooters become motorized, our proof of concept centered around the brushless hub motor. In a hubmotor, the motor and wheel are self-contained in the same assembly – an inherently portable design that allows them to be attached and detached from various vehicles. Unlike brushed motors, the rotor contains permanent magnets in the center of the motor and electromagnets are placed in the stator surrounding it. A motor controller switches the polarity of the surrounding electromagnets, causing the rotor to turn (Fig. 5). These motors tend to save energy when compared with brushless dc motors, and have been widely adopted by various Ebike companies such as Lime [2] and The Copenhagen Wheel [3], the latter of which included means to recapture energy dissipated while cycling and braking.

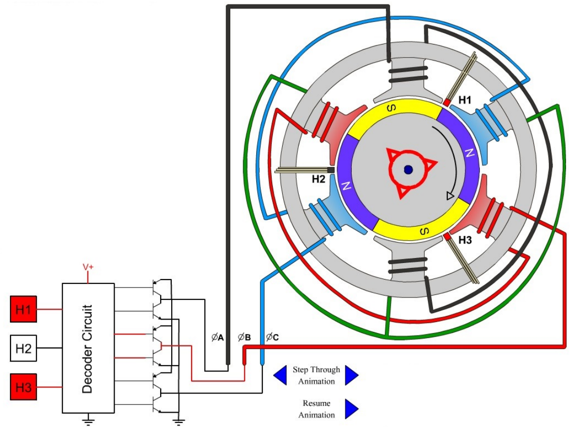

Fig. 5. Operation principle of a brushless hub motor, (Figure from [1]). A motor controller switches the polarities of electromagnets surrounding the rotor, causing it to spin

To ensure standard hubmotors could handle typical loads of the cart, we asked community members to pull the cart using a luggage scale and report the reading. An average of 25 kg was read without any weight on the cart, and it was estimated the cart would carry up to 150 kgs at a time. We assume the average person can push up to 10kg of the load, which would leave about 15kg of force F_{motor} to be supplied from the motor. We also fixed the speed of the cart to be constant around 1.35 m/s, which is about a 20 minute mile (suitable for walking speed).

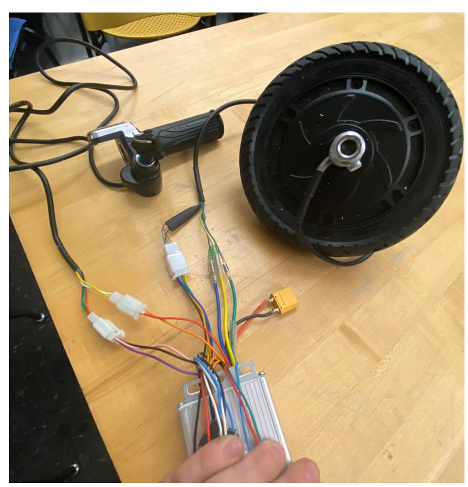

Fig. 6. Commercially available brushless hubmotor

Due to prototyping constraints, we decided to test our proposed solution by augmenting our replicated wheel cart with a commercially available brushless hub motor [1]. To determine the suitable weight ceiling for a standard 48V, 350W brushless hub motor (Fig. 6), we analyzed its torque and power capabilities at walking speed ($1.35\frac{m}{s}$).

The power of the motor is related to its torque and angular velocity by:

$$P = \tau \cdot \omega$$

where $P = 350\,\text{W}$ is the motor power, τ is the torque (Nm), and ω is the angular velocity (rad/s). The angular velocity can be expressed in terms of the linear speed v and the radius of the motor's driving wheel r_{drive}:

$$\omega = \frac{v}{r_{\text{drive}}}.$$

Substituting for ω, the torque is:

$$\tau = \frac{P \cdot r_{\text{drive}}}{v}.$$

Using $P = 350\,\text{W}$, $r_{\text{drive}} = 0.04\,\text{m}$, and $v = 1.35\,\text{m/s}$, we calculate:

$$\tau = \frac{350 \cdot 0.04}{1.35} \approx 10.37\,\text{Nm}.$$

Thus, the maximum torque the motor can supply is approximately $10.37\,\text{Nm}$.

The force generated by the motor at the wheel is related to its torque by:

$$F_{\text{max}} = \frac{\tau}{r_{\text{drive}}}.$$

Substituting $\tau = 10.37\,\text{Nm}$ and $r_{\text{drive}} = 0.04\,\text{m}$, we find:

$$F_{\text{max}} = \frac{10.37}{0.04} \approx 259.25\,\text{N}.$$

The motor can supply a maximum force of approximately $259.25\,\text{N}$.

The weight ceiling corresponds to the maximum mass m the motor can move, given the rolling resistance force:

$$F_{\text{resistive}} = m \cdot g \cdot \mu_r,$$

where $g = 9.81\,\text{m/s}^2$ is the acceleration due to gravity and $\mu_r = 0.02$ is the rolling resistance coefficient. Equating $F_{\text{resistive}} \leq F_{\text{max}}$, we solve for m:

$$m \leq \frac{F_{\text{max}}}{g \cdot \mu_r}.$$

Substituting $F_{\text{max}} = 259.25\,\text{N}$, $g = 9.81\,\text{m/s}^2$, and $\mu_r = 0.02$:

$$m \leq \frac{259.25}{9.81 \cdot 0.02} = \frac{259.25}{0.1962} \approx 1322.2\,\text{kg}.$$

Thus, the motor can theoretically handle up to $1322.2\,\text{kg}$ under ideal conditions. We plan to progressively load test the motor, and see how it operates under smaller operating powers.

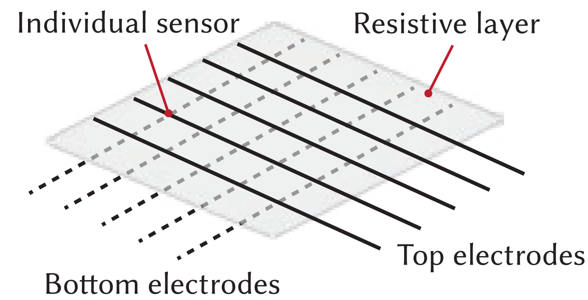

Fig. 7. Typical layout of a resistive matrix-based pressure sensing form factor, with a resistive layer sandwiched between two sets of orthogonally positioned electrodes.

C. Textile-based Pressure Sensing

To automatically weigh items on the cart in a digital manner, we looked towards low-cost weight sensing solutions. Resistive matrix-based sensing has emerged as a low-cost means of observing pressure changes due to applied normal forces. The principle works by organizing two orthogonally positioned series of electrodes on either side of a piezoresistive material. Sensing units are formed at the intersection of each row wire and column wire, and pressure signals are read through the change in resistance of the top wire and bottom wire (Fig. 7).

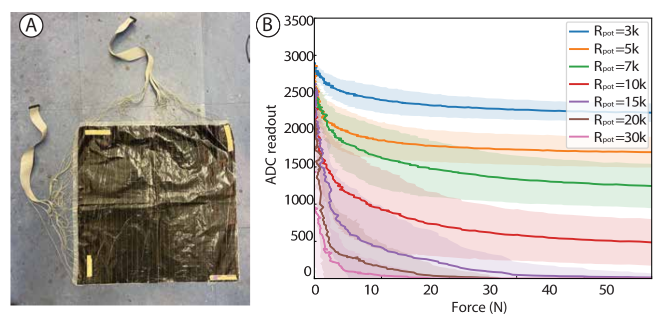

Fig. 8. A) Pressure sensign mat, fabricated by taping conductive thread onto Velostat B) Force vs Analog voltage for different potentiometer values, showing sensitivity up to 50N

We fabricated these sensors by directly taping conductive thread onto commercially available Velostat for less than 5 USD per square foot. We also developed a zero-potential readout circuit around the ESP32 microcontroller, and use it to read and wirelessly send pressure data across the mat via bluetooth. Using a digital potentiometer to control sensitivity, our initial test demonstrates the potential for the sensor to weigh up to 50N (10 lbs) per square inch (8).

IV. Evaluation

The team will carry out a planned evaluation to collect observations and user feedback on the design. We will use the Observe Ask Try (OAT) methodologies:

[1]https://www.amazon.com/Electric-Scooter-Conversion-Brushless-Accessory/dp/B08R3W634R

- **Observe:**
  - Create a map of the Imvepi Camp, including resources, spaces, and systems that would be relevant to a wheel cart user, such as the location of the market.
  - Watch the wheel cart user's interactions with the wheel cart, including movements and body language. Pay attention to the surrounding environment and sounds.
  - Take photos and videos to reconstruct the environment, after asking for permission from users and community members.
  - Shadow a user for a day as they find customers at the market and deliver goods using the wheel cart.
- **Ask:** We will survey community members with the following questions, evaluated on a 5 point Likert Scale.
  - *"How easy is it to use the motorized cart compared to manually pushing a traditional wheel cart?"* (Scale: Very difficult-Very easy)
  - *"The motorized cart reduced the physical strain of transporting goods over long distances?"* (Scale: Strongly agree-Strongly disagree)
  - *"The load weighing system is reliable and will help price trips"* (Scale: Strongly agree-Strongly disagree)
  - *"Adding these modifications to existing wheel carts will be possible using local resources"* (Scale: Strongly agree-Strongly disagree)
- **Try:**
  - Do it yourself: Weigh items with the textile-based pressure sensor and push the cart ourselves with the motorized extension.
  - Extended immersion: Assist a wheel cart pusher in transporting goods for a customer.
  - User engagement: Try out the wheel cart with the users.

V. Conclusion

The introduction of a motorized wheel cart and accompanying low-cost technology for load measurement presents a promising opportunity to alleviate the physical burden faced by Ugandan refugees at the Imvepi camp and enhance their business operations. By addressing the challenges of manual load transport and incorporating a practical system for weight-based pricing, this initiative has the potential to improve economic efficiency and quality of life. Future efforts will focus on the development of an Android application for real-time load monitoring, as well as evaluating the motorized cart's carrying capacity and the feasibility of using local resources to power the cart.

References

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