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DESIGN OF HUMAN-POWERED HYBRID ELECTRIC-POWER SHOVEL FOR DEEP EXCAVATION

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Abstract

There are still a lot of high-load physical works which can't be substituted by machine, such as clearing snow, removing sediment under floor and volcanic ashes, where a large-sized machine cannot be used or where human resources and electric power were short on occasions of emergency. Therefore, authors address to design a device for those situation. Authors focus on unique approach of "human-powered hybrid" method combining merits of human-power and machine-power. In this paper, we made this approach clear as a design method, which suggest 3 policies: choose a heavy equipment suitable to targeted work, apply human-power to each work process, and consider usability. And we apply these policies to new device for removing earth-and-sand under floor as a specific situation. Then we designed and constructed it that can excavate while switching human-power or machine-power. Users can operate it semi-automatically without pre-training, and can operate it in safety not to fall over by incorporating mechanical and electrical structures. Finally, we conducted performance experiments and confirmed that the device could work efficiently not only with human-power but also with machine-power.

Keywords: Design engineering, Design methods, Design process, Mechatronics, User centred design

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1 INTRODUCTION

Many human activities require heavy physical works as in construction and agriculture. And indeed, some of those activities have been gradually replaced by machines such as excavators. Yet, there remains activities which still solely rely on human strength. Such activities often occur after a natural disaster, for example, removing dirt from a ditch and underneath housing after flooding caused by a typhoon or even ashes in the streets after a volcanic eruption. Around those disaster sites, existing heavy machineries often can't be transported by truck due to rough road condition and can't also be used in a building because of their heavy weight and exhaust gas. Then, when scale of disaster is large, heavy machineries are not necessarily deployed in residential area and the number of heavy machinery often becomes insufficient. In addition, there is a shortage of fuel in the case of natural disasters.

Responding to those problems, various wearable robots would reduce physical load instead of using heavy machinery. For example, to relieve aged farmers from the discomforts of squatting and having their arms extended for long periods, a device with motorized joints has been developed (Toyama, 2010). Military-wise, exosuits are pursued for transporting heavy loads (Adam, 2006) as well as full body suits (Marchechi, 2011) Then, hydraulic wearable robots begin to be used in shipbuilding work (Chu, 2014). On the other hand, passive-wearable robots have also been developed (Hong, 2014).

While the developments of such wearable robots will be promising, they cannot respond to a major catastrophe suffering from a shortage of resources and need expedite response. In such situations, non-wearable tool would be preferable, as they could be adapted quickly to a variety of user body size thus making it ideal for working in shifts. Tools such as ASTACO was utilized for construction work during earthquake disaster (Ishii, 2006).

The author's group has focused on designing a device for physical work that still requires manpower and where a non-wearable is more useful. Then we've investigated a design approach of work tool which has both merits of human-power and of machine-power for excavating work with large physical load. In this study, we consider the further possibility of the approach and devise the tool which is intended for more burdensome excavation work.

2 METHOD

2.1 Previously suggested ideas

We focused on a particular type of excavation work. The niche is situated in that the performance in working loads, hours and efficiency indicates more than using a tool such as scoop and less than using hydraulic work machine such as ultra-mini hydraulic shovel. We suppose that users operating a device in that niche can work for longer periods, while requiring fewer people and increasing the scooping load (average:3[kg], maximum:5[kg]) compared to typical human-powered scooping. Meanwhile, they will also perform less work than machine-powered work equipped with engine and hydraulic actuator (e.g.: micro shovel, weight: 300 [kg], struck capacity: 13.6 [kg] (KOMATSU, 2012)). In such niche, there are few tools for high-load construction work, e.g.: cultivator or snowplough with electric motor or gas-powered engine. We have considered about new idea to increase a variety of tools.

We have suggested ideas in two directions. The first idea focuses on supporting only high-load action in excavation work using a scoop, or to assist lifting (Iwamoto, 2013). As shown in Figure 1a, the device we devised previously rests on the ground with three legs and lifts the arm with a scoop actuated by an electric motor. Additionally, in order to avoid the user having to crouch over as in traditional shovelling, our tool assures that user can keep on working in upright position and can instead lift the shovel by pushing a pedal transmitting force through via a moving pulley (Figure 1b). These devises are designed based on how human-powered work with tool is substituted by a machine, in other words the idea indicates a direction of "from tool to machine". In this region, tools and researches to support physical work are relatively popular and increasing wearable robots are included in this area.

The second idea is to focus on power shovel itself for excavation, and to adapt it for human scale (Fujisawa, 2015). Following that reasoning, we developed a novel human-powered excavator where the users manipulate the arm and boom directly while lifting a bucket with heavy load with motor-assistance (Figure 1c). We designed the excavator based on the following idea. If all the operations were to be mechanically actuated, the excavator's size and weight would increase as motor output would then too increase. On the other hand, if all the workload has to be fulfilled by manpower alone, the load on a user would increase. Therefore, we designed that only high-load lift operation is provided by machine-power while the user performs the other less intensive load operations. Then, we suggested to blend the merits of manpower and machinery in a single machine. This idea contrasts to the former "from tool to machine" idea and can be viewed as “from machine to tool”.

2.2 Design of human-powered hybrid electric power shovel for deep excavation

The authors consider that the idea of “human-powered hybrid” blending merits of human-power and machine-power is unique with perhaps the exception of electric power-assisted bicycles. Therefore, in this paper, we explore the further possibility through applying the idea to another physical work with much heavier load, and through developing a device for the work and investigating performance by using. Our former device was intended for excavation work only near ground level such as shovelling away a pile of dirt into a wheelbarrow. This time, we focused on “deep excavation” which enables the user to shovel below ground level as when shovelling out a ditch.

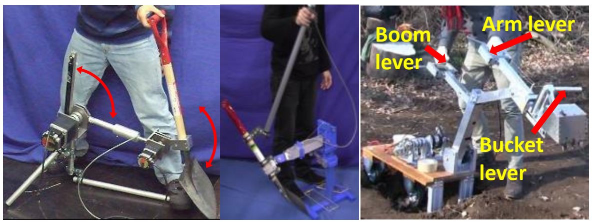
In the developmental process of our former device, first we chose a type of excavator simply and considered how human-power was applied to motion of excavator, and added handles to an arm and a boom so that users can manipulate them directly. We supposed that a user can feel as if the user handled just a large scoop when the user manipulates the excavator. Then we investigated how our excavator was manipulated and found that it was necessary to consider usability especially relating to using both hands and feet because a user had to keep the positions of arm and boom by locking and to switch hands with difficulty when handling a bucket.

For making the above considered idea clear to utilize it as design approach, we suggest three policies to design a human-powered hybrid construction equipment:

1. To choose an original type of construction equipment corresponding to targeted work.
2. To apply human-power work to each process of the construction equipment.
3. To incorporate operation method considering usability.

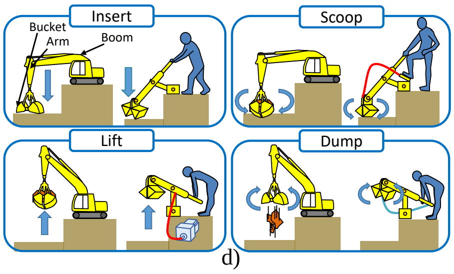
Based on these policies, we designed a novel construction equipment for “deep excavation” as heavier physical work.

1) To choose an original type of construction equipment corresponding to targeted work Authors focused on a clam-shell shovel for “deep excavation”. As shown in Figure 2, the shovel consists of arm, boom, and bucket similar to a common power shovel. Especially, the bucket is different from a common type that has only one side. Two buckets are located opposite each other and move like clam-shell. Then it is possible to excavate by opening and closing two buckets simultaneously. Therefore, clam-shell bucket allows vertical excavation below surface of the ground and we consider that clam-shell is suitable to work "deep excavation".



a) b) c)

Figure 1. Previous devices: a) Assisting in lifting by electric motor, b) Assisting in keeping upright position by transmitting mechanism, c) Human-powered hybrid device



d)

Figure 2. d) Four phases in excavating with clam-shell shovel

2) To apply human-power work to each process of the construction equipment.

The use of a clam-shell bucket shovel can be segmented into four phases as shown in Figure 2: First, a user moves the bucket to the targeted excavating position, secondly, by closing the bucket digs up the soil, thirdly lifts it and finally dumps it at a predetermined place by opening the bucket. In each of the four phases, we consider how a combination of human-power and machine-power is designed to maximize the merits of both human-dexterity and machine-power.

A clam-shell excavator inserts the bucket into soil by swinging down the bucket and its arm. This motion is typically supplied by hydraulic motor. However, since the bucket and arm moves downward, the device's own weight can be used. Thus, we consider that this swinging down motion can be applied by human-power.

Secondly, a clam-shell shovel scoops while closing two buckets. Therefore, this motion needs a larger excavation force. If this scooping were provided only by actuator, the device's size and weight will increase depending on load. Therefore, by providing human-power utilizing a user's own weight, it is expected that the device will lead to be miniaturized than only utilizing machine-power.

Thirdly, lift is a work to elevate payloads in a bucket to targeted height which a user wants to load and is done against gravity. Because the weight of not only the payload but also the arm and the boom are added to loads of work, machine-power is required more than number of payloads. Additionally, it should be possible to increase device's lift speed and range by adding human-power when users feel that a machine output became insufficient and that lifting speed is low. Thus, we propose combining human-power and machine-power in lift operation.

Finally, because dump operation consists of simply opening a bucket, we consider that an additional mechanical power is unnecessary. Additionally, because payloads of bucket fall downwards, or users make use of soil's itself weight, applying human-power to dump operation has merit.

As a wheelbarrow, the whole shovel system can be rotated and displaced by hand.

3) To incorporate operation method considering usability

We examine operation methods considering usability. In order to design how to move bucket, arm and boom of previous developed device manually, authors focused on a toy shovel for sandboxes. As shown in Figure 1c, 3a, we attached a lever to each of arm, boom and bucket so that users operate an arm and a boom for moving to an excavating position with both hands and for manipulating a bucket near surface of the ground with foot. However, in experimental excavation work, when users manipulated the arm and boom by grasping both the arm and the boom our users found it very difficult to control the position of the shovel. We found that it is necessary to consider the flexibility for manipulating the device's attitude. Therefore, as shown in Figure 3a, we designed another arm where only one-hand manipulates movements of both of the arm and boom with the assistance of an actuator while another hand operates the device's body for stability. Real bucket operation is controlled via a lever operation and continuous adjustments are required. Then, in previous developed device, it was difficult to conduct this operation only by one-foot. This bucket operation needs power but should be simple for considering usability. Additionally, an excavating position is not located under user's foot. Thus, we attached a pedal near the device's base and pealing force provided by a user's own weight transmits to a bucket operation.

For switching human-power or machine-power, we incorporate a mechanism that enables a user to excavate continuously without disengaging user's hands from handle by providing a selecting switch near handle. Then, we consider the function for which users can operate without practicing it beforehand. When scooping up a lot of dirt, the reaction force is caused by inserting a bucket into the ground deeply. If excavating power was provided by high power actuator and with a high stiffness bucket, it will be possible to excavate against high dirt reaction force. In order to downsize a device and to trim weight, dirt reaction force should be reduced. Therefore, we focus on a technique in actual excavating work with a power shovel, in which the arm, boom, and bucket are operated simultaneously to scoop up as many dirt as possible while reducing reaction force as shown in Figure 3b. Such composite-operation requires much experience and operation skill. When disaster occurred, an engineer and an operator who can do such operation isn't usually readily available. Thus, we incorporated an assistive function reducing the skill required for composite-operation.

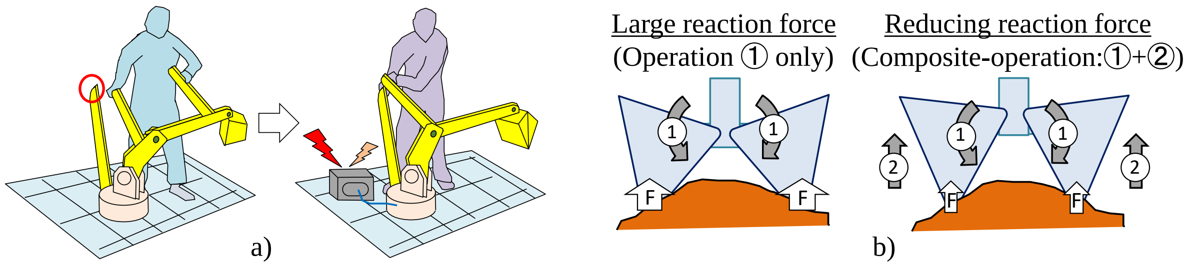


Figure 3. Consideration in operation: a) how to manipulate an arm, a boom and a base with both hands, b) composite operation to reduce earth-and-sand reaction force to a bucket

3 DESIGN AND DEVELOPMENT

We set out a specific workplace to work on device design. A typical scenario that employs deep excavation is clearing away dirt underneath housing after flooding. Note that removing dirt sometimes can be done by a sludge suction vehicle when sludge can be vacuumed. However, such heavy and expensive equipment isn't easily accessible, and then such work must be normally done by human-power of a lot of volunteers. Our device is designed for such tasks. There is an ultra-micro shovel that can lower to the depth of the underfloor. However, it is often difficult to use the shovel indoor because it has a risk that floor crumbles due to weight of device (300 kg) and exhaust gas. Moreover, because it is not deployed among general households, basically, humans must work with scoops. It is a very convenient situation to suggest new device that have solve the problems.

Then, each value of device specifications is prescribed based on a work of loading dirt of underfloor onto a wheelbarrow by using a scoop and discharging dirt outside. The maximum dumping height of our device is over 600 [mm], that is, the average height of a wheelbarrow. Since the height from the ground to the floor is required to be more than 450 [mm] by the Building Standard Law in Japan, the maximum excavating depth indicates 450 [mm]. The bucket capacity is estimated based on amounts of excavation per typical shovel (maximum: 3[L], average: 2[L]). Since the commercial smallest micro shovel weighs 300 [kg], a light truck etc. is generally required for transport. Yet our device should be below this weight and be a size which single person can also carry all by itself. Thus, based on the Road Traffic Law in Japan, the device is designed below 30 [kg] such that it can be loaded onto a bicycle luggage rack. Additionally, work speed is preferably below 250 [mm/s] based on the speed currently recommended for a cooperative work between human and a robot (Mukaidono, 2013).

As shown in Figure 4a, this device consists of a bucket to hold and scoop, an arm and a boom to move the bucket easily, a base to sustain the arm and boom and to move the whole device, and operation unit to manipulate each part.

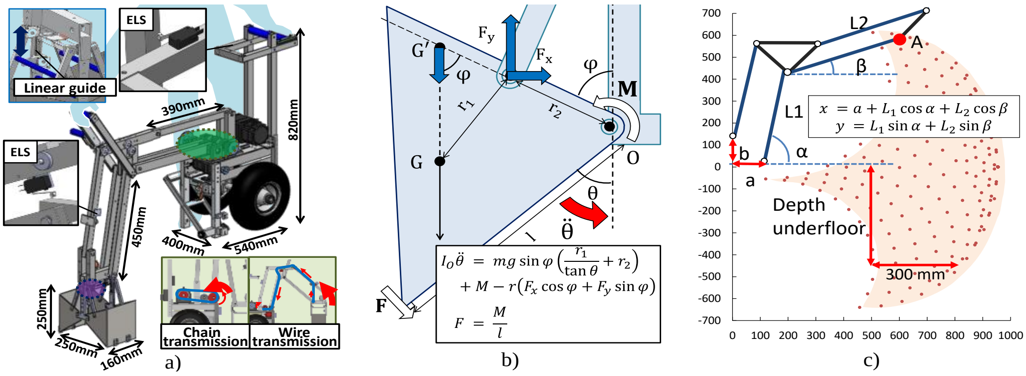
The size of the bucket was determined by downsizing a commercial clamshell bucket as similar shape so that each value of specifications can be fulfilled. Then we measured pedalling force with crane scale and it indicated approximately 73[N]. By importing the CAD data of bucket to MATLAB, bucket closing was simulated on the condition of giving 73 [N] for 1 second. The bucket was made of 1-mm stainless plate because of its high rigidity yet sufficiently fin to be easily dug into the ground. As shown in Figure 4ab, a bucket keeps in open by pulling up a bucket with a constant load spring (2.4 [kgf]) before excavating. Pressing on the pedal moves a slider attached on bucket upward, and the movement of slider rotates a bucket. When releasing the pedal, the bucket closes due to its own weight.

Since the clamshell bucket constantly needs to be kept in vertical attitude at the tip of arm, a parallel linkage mechanism is incorporated to arm-boom structure. The size of arm and boom was decided to fulfil the aforementioned excavation range, and a movable range was especially designed to be over 300 [mm] in x direction under floor in Figure 4c. In addition, since a light weight and rigidity were required for arm and boom, they were mainly made of a square pipe (2.5 [mm]) of an aluminium alloy. The rotation axis of the end was of a rigid stainless alloy (φ10 [mm]).

By mounting the comparatively heavy actuators and batteries near the base, the center of gravity of the device can be lowered for enhanced stability. In order to turn the device around in narrow space unrestrictedly, two wheels are mounted on the base (φ293 [mm], width 96 [mm]). Then, the size of base and arrangement of parts are designed such that there is no risk of the device turning over. The base is made of an aluminium alloy (4 [mm]).

The arm and boom are driven by a stepping motor (at the arm: maximum torque 20 [Nm] and rotation speed 0-83 [rpm], for the boom: max. 60 [Nm] and 0-56 [rpm]). Since the arm is distant from the motor, the drive force is transmitted via a wire. In contrast, the drive force for boom is transmitted via chain because of near. Concerning the battery, it is assumed that a battery of electric power-assisted bicycle for carrying this device is also used as device’s battery. The lithium polymer battery (voltage: 22.2 [V], capacity: 10000 [mAh]), light, small and high output, was used in this prototype device.

Let us next explain how the unit operates: opening and closing the bucket is performed by pedalling. Then, since the pedal itself falls under its own weight, a constant load spring (0.6 [kgf]) pulls up the pedal so that users can pedal. The arm and boom are operated by one handle leaned 45 degree and attached onto the arm shown in Figure 4. Since this handle is fixed only onto the arm, a user can move both arm and boom connected to the edge of the arm simultaneously. That is, when a user moves the



a) b) c)

Figure 4. Human-powered hybrid electric power shovel for deep excavation: a) whole structure of the device (30 kg), b) Bucket model (F_x, F_y and $\ddot{\theta}$ are simulated by MATLAB. Bucket's moment of inertia:I_O, mass: m, Gravitational acceleration:g), c) Movable range of arm-boom model (Tip of an arm: A, arm length:445 mm, boom length:390 mm

handle horizontally and vertically, the boom is operated and the arm follows. Then, when a user rotates the handle, the arm rotates at the position where the boom is located.

By manipulating this handle a user can move the position of bucket freely with one hand. Then by manipulating another handle attached to the base with another hand, a user can move and support the device. Additionally, a user can adjust speed of arm and boom movement and switch either operation of arm and boom by human-powered or by machine-powered when pushing a switch attached to these handle grips so that a user can operate it continuously without releasing hands. Signals of these switches are inputted into a microcomputer board, and pulse waveform is outputted from the computer to a motor through a motor driver in machine-powered mode. Then, safety function for users and for preventing destruction of device was also taken in it. When the arm or boom contacts with end-limit-sensor located at the movable limit of arm and boom, a stop signal is inputted into the motor driver and the motor stops compulsorily. Additionally, each signal of pressure sensor for detecting pedalling and acceleration sensor for detecting positions of arm and boom are transmitted to a microcomputer board to control motors.

Finally, we explain abovementioned mechanisms according to four phases in excavating (Figure 5). In inserting phase, it is assumed that a user can operate arm and boom by only human-power utilizing the arm-boom's itself weight so that a bucket can be swung down toward the direction of gravitational force. On the other hand in actual excavating situation, it is necessary that a user keeps on holding an arm, a boom and a bucket until moving to an excavating position. Therefore, because such physical load is high for a user, we design that a user can perform insert operation by not only human-powered but also by machine-powered. That is, the arm and boom can be operated with assisting motor which can drive while a user turns on a push switch.

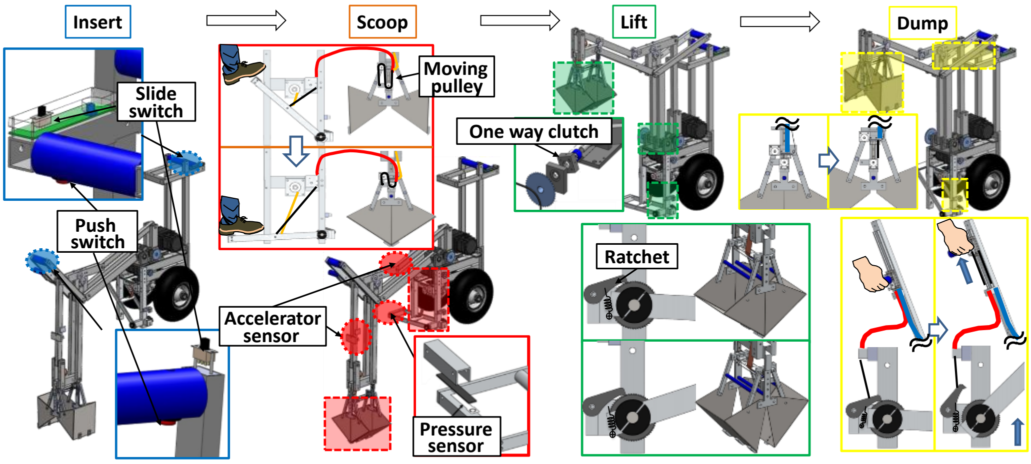


Figure 5. Mechanisms according to each of 4 phases in excavating

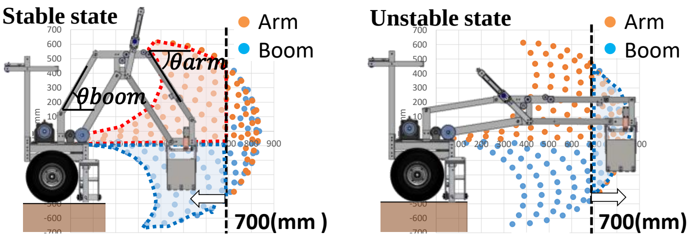
In scooping phase, the bucket is closed by transmitting pedalling force to it through a wire. In addition, excavation force is doubled by a moving pulley incorporated in wire-traction mechanism. If a user pedalled forcibly and tried to keep on scooping, dirt reaction force might break a wire. Therefore, the arm and boom can be moved upwards semi-automatically by controlling motor to reduce dirt reaction force and grab dirt as much as possible. As shown in Figure 5, this operation is performed based on pedalling force measured by pressure sensor. Then, the threshold value for operating this function was determined through exploratory experiment.

In lifting phase, if an arm and a boom are moved upward in a state as shown in Figure 6 (right), the device might fall over because the gravity center of device shifts toward a bucket with load. Therefore, we design how to control semi-automatically movements of an arm and a boom respectively according to the position of a bucket. At positions of Figure 6(left), since a gravity center is stable, an arm or a boom can move to lift a bucket. We examine that either arm or boom can move to lift toward the vertical direction. The discriminant is given as follows Figure 6 formula (1). ΔY_{arm} and ΔY_{boom} show amount of movement of an arm and a boom respectively toward the vertical direction. When $\Delta Y_{arm} > \Delta Y_{boom}$, an arm should move to lift. When $\Delta Y_{arm} < \Delta Y_{boom}$, a boom should move. In contrast at positions of Figure 6(right), only a boom should move to lift. The discriminant at that time is given as follows Figure 6 formula (2).

Positions of an arm and a boom are measured by an acceleration sensor. Then, after a user turns on a switch to drive a motor so that the arm and boom move to lift, user's operation is similar as inserting operation. Especially, since a one-way clutch is incorporated into a driving shaft of boom, it is possible to add human-power to machine-power when a user wants to move much faster and lift much heavier load. Additionally, as shown in Figure 5, a bucket can hold at arbitrary angles because a ratchet is incorporated into the pedal. Therefore, it is possible to keep on holding a soil even when a user takes a foot off the pedal or when a bucket cannot close completely because of overflowing a pebble and a piece of wood through chink.

In dumping phase, as shown in Figure 5, when a user pulls a lever for ratchet, the bucket is opened by force of a constant load spring holding a pedal and load itself weight.

As mentioned above, we designed and constructed the human-powered hybrid excavation device which weighs 30 [kg] including battery, which can be loaded onto a bicycle and which is took into consideration usability without special pre-training.



$$(1)\quad \begin{aligned} \Delta Y_{arm} &= L_1 \sin\theta_{boom} + L_2 \sin(\theta_{arm} + 1), \\ \Delta Y_{boom} &= L_1 \sin(\theta_{boom} + 1) + L_2 \sin\theta_{arm} \end{aligned}$$

$$(2)\; L_1 \cos\theta_{boom} + L_2 \cos\theta_{arm} \geq 700$$

Figure 6. Judgement of manipulation depending on bucket position (Blue points show that the boom moves to the vertical direction rather than the arm. Orange points indicate opposite way. When the bucket is located over 700 mm in x-direction, it is found that orange points are intermingled with blue points.)

4 EXPERIMENT

4.1 Performance

We verified whether the bucket can move at a set speed. At the beginning, we operated the device at an almost maximum speed 250 [mm/s] as recommended (Mukaidono, 2013), and we found that it was too fast to manipulate it and it might be dangerous because we could not keep on handling it. Therefore, speed was set to 50, 100, 125, 150, 200 [mm/s]. Each speed of an arm and a boom, which lifted to 120 degrees or moved to limit of an arm-boom, was calculated from data captured by three-dimensional position measurement system (OptiTrack). The boom can move at set speed stably, while an arm speed exceeds a target speed on condition of more than 125 [mm/s] when an arm begins to move in Figure 7. We consider this is because rotary inertia when a drum starts reeling wire has influence increasing movement speed.

About duration time of driving motor, we operated the device half a day in experiment mentioned later. Thus, it is expected that it will be possible to work continuously for at least 7 hours.

We measured motion of the tip of arm while the arm and boom lifted to 120 degrees by three-dimensional position measurement system (OptiTrack). Figure 8 shows measured movements and theoretical movements. Although there was about 80 [mm] difference at the maximum between both positions under a floor, it is found that actual trajectory seems to be almost similar to theoretical one and confirmed to fulfil specifications value.

We measured excavating force by pinching force sensor at the tip of bucket and it show approximately 50[N]. Theoretical excavating force is calculated as almost 52[N] by considering a constant load spring to cancel the bucket's own weight and amplifying mechanism when opening angles of the bucket is 7 degrees. It is confirmed that measured force is almost close to the theoretical value.

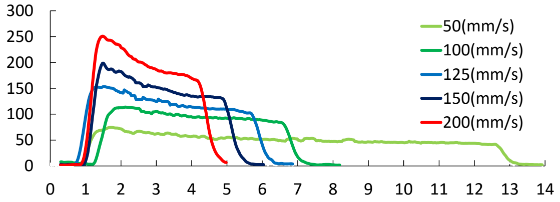


Figure 7. Experimental results of arm speed

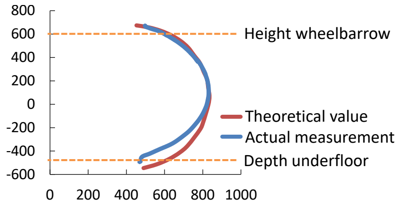


Figure 8. Movable region of the tip of arm

4.2 Manipulation

It was verified whether users, or developers skilled in operation, could actually excavate in the environment shown in Figure 9. Considering safety to users, the arm and boom speed was set to 50[mm/s] and users conducted excavating ten times. Amounts of excavation were examined by measuring weight of soil dumped in the case. A specific gravity (0.9 [kg/L]) of a soil was measured by putting a soil into a 1L-case, and a volume of an excavated soil was converted from it. It is confirmed that amounts of soil excavated by using the device almost exceed average amounts of soil, or 2[L], by using typical shovel manually (Weight: Average=2.2kg, SD=0.58, Volume: Average=2.5kg, SD=0.63). Then, developers tried to conduct a sequence of excavation only manually without motor assist. We confirmed that it is possible to work in a situation without any power sources other than human-power. We assumed a work situation of removing dirt under floor and we examined how the device worked in excavating. We focused on amounts of excavated dirt and operate time during which users begin to move at initial position on a foundation, insert a bucket into dirt, lift and dump it into the case at the height of which is supposed at wheelbarrow. We, 4 developers skilled in operation also conducted this task under 6 conditions of 5 working speeds with motor assisted and without assistance. Working speed was set to 50, 100, 125, 150, 200 [mm/s] and users excavated 5 times under each speed condition.

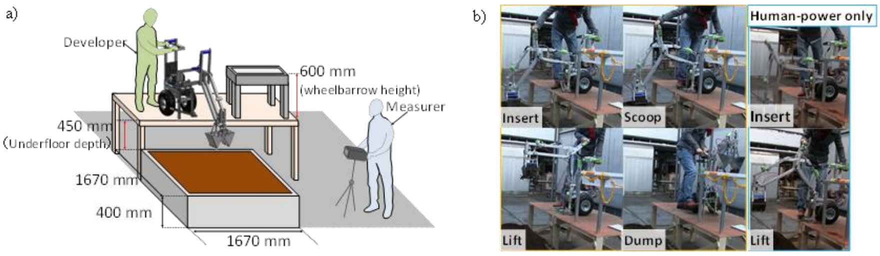


Figure 9. Excavating experiment: a) Experiment environment, b) Scenes of excavating work

Figure 10a and 10b show the results of amounts of averaged excavated dirt and operate time. Additionally, excavating efficiency is shown in Figure 10c calculated from excavated amount per unit time. Figure 10a shows that there was no significant difference among working speed in amounts of excavated dirt as a result of analysis of variance. Then, operate time gets shorter with the rise of working speed. Therefore, it is found that excavation efficiency rises depending on increasing speed. Then, the minimum of the averaged standard deviation in operation time indicates 2.6 under 150 [mm/s] condition. Based on this result that there is less individual difference under the condition of 150 [mm/s], we consider that this device should be available not under maximum speed condition when variety of users, including people who don't exploit well, use the device for a short time. In contrast, when a few users keep on working for a long time, this device will be effective under high speed condition to increase excavation efficiency by taking into consideration of skill in operation.

In case that users will have to work on excavating in a situation of electric power shortage on occasions of emergency, we developers excavated only manually without motor assisted. At this trial, we operated this device as soon as possible purposefully. The results of both excavation efficiency and operation time under manual condition are similar to under the condition of 200 [mm/s]. We consider it is because operators could insert deeply in short time by utilizing falling the arm and boom freely under its own weight. However, these results just come from task for about 5 minutes at most. As far as we excavated deeply by using this device manually, we feel that it is terribly hard to keep on working more than 5 minutes continuously. Furthermore, it will be much harder to excavate and lift load at nearly 1 [m] by using typical shovel manually. We confirmed certainly that assistance of machine-power is effective for continuous excavating work and that the device can effectively perform excavating work including lifting at nearly 1 [m] as removing dirt under floor.

After this, we continue examining evaluations of excavating work by users who operate the device for the first time and performances of excavating dirt including not only soils but also mixed gravels and woods, and finally we aim to develop a device available for real situation.

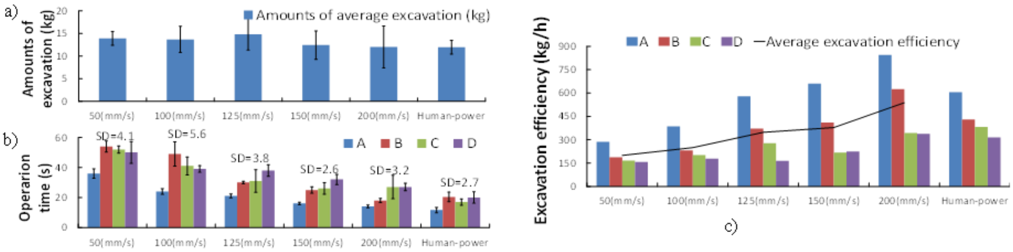


Figure 10. Experimental results: a) Amounts of excavated soil, b) Operation time, c)Excavation efficiency

5 CONSIDERATION

We mainly consider the approach to design a tool for construction work in a niche where our design outperforms traditional hand tools yet can perform less than "micro" heavy machinery. The work in this area includes not only digging soil but also collecting, lifting and ploughing it. Recently, increasing wearable robots assisting motions are positioned in the same area. Meanwhile, in this field of research, alternatives to such exoskeletons remain scarce. There are still many situations in which manpower is required especially such as working in a narrow space, indoor and in a situation out of fuel. Therefore, it is expected that a variety of tools contribute. Then, we propose an approach that can outline a device corresponding to each task in common. This means that people doesn't need to design a tool corresponding to each task from the beginning. In other words, we consider that the approach gives "primitive form" of the working tool. Then, we focused on general construction equipment as such primitive prototype. For example, if we consider removing ashes, a machine similar to a snowplough would expel large ash clouds. Hence in this situation a machine that scrapes away the ashes is preferred. In this case, a motor grader might be chosen for only turning aside ash to road, or a wheel loader might be chosen to scrape and throw away ashes at a parking as a primitive prototype. Excellent construction machinery has evolved for decades and with optimized structures, mechanisms and layouts, that can be a source of inspiration for designing a new device.

Then, such a "primitive form" is applied in an operator-friendly way. In this process, we consider that it's relatively easy to blend movement of construction equipment to humans, because most of construction equipment have arms and joints mimicking the human body. For example, children can behave like a power shovel by moving arm in playing with sand. Additionally, we also consider that it's easy to imagine how our machine works since people can often observe construction equipment in their daily lives and build mental models from those experiences. This leads us to think that novice users, thanks to those mental models, could be able to operate our device without any previous training. This is the advantage of recycling the general layout of construction equipment as "primitive form".

Moreover, blending human-power and machine-power permits the actuators to be downsized. Especially when the device moves in direction of gravitational force, the blended system can output effectively because own weight of a user and the device though it uses small actuator.

In the future, even when lighter and compacter actuators are developed, this approach will remain promising at that time to develop potential of the device as another option. For example, if electric power or fuel runs out, the equipment based on such an approach can continue to work manually while being more effective the using traditional tools. Such design of a device that works effectively rather than conventional tools will be supported by existing design tool, such as TRIZ.

Meanwhile, there is sometimes a gap between actual real motions generated by construction equipment and the novice's mental models. For power-shovels, some novices tend to operate the bucket only without using arm operation while using our previous device. And, the users lifted the clamshell only after it was completely closed whereas a real machine does this task by simultaneously closing and retracting the shovel. Those operations differ from real excavators and doesn’t work well. As our current device conducts those operations automatically, those mis-interpreted operations can effectively be avoided.

In future works, we will investigate how people translate motions of heavy machinery to human motion and then we will formulate the relation by considering real operations of heavy machinery dynamically. Finally, the current approach will be a method to design an equipment exploiting human performance and blending it to machine in above mentioned niche.

6 CONCLUSION

We examined an approach to design a device which assists a heavy physical work in a situation where construction equipment cannot be used or where human resources and electric power were short. Especially we focused on our unique idea of “human-powered hybrid” proposed previously.

Firstly, we made the previous idea clear to utilize it as a design approach by suggesting 3 policies: choosing a construction equipment corresponding to targeted work, applying human-power work to each process, and considering usability. Secondly, we apply these policies to design new excavating device for removing dirt under floor as a specific situation. Thirdly, we designed and constructed a device that users can excavate while switching human-powered or machine-powered, users can operate it semi-automatically in complicated operations without pre-training, and users can operate it in safety not to fall over by incorporating mechanical and electrical structures. Finally, we conducted performance experiments whether fulfilling each value of specifications and under various speed conditions including without machine-power. Then we confirmed that the device could work in an efficient way by blending symbiotically human-power with machine-power.

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