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HOUDINI: SITE AND LOCOMOTION ANALYSIS-DRIVEN DESIGN OF AN IN-TANK MOBILE CLEANUP ROBOT

Hagen Schempf
Carnegie Mellon University
FRC 201, 5000 Forbes Ave.
Pittsburgh, PA 15213
(412) 268-6884, 268-5895 FAX E-mail: hagen+@cmu.edu

ABSTRACT

This paper describes design and locomotion analysis efforts to develop a new reconfigurable and collapsible working machine, dubbed *Houdini* (see Figure 1), to remotely clean up hazardous-waste and petroleum storage tanks. The tethered robot system is designed to allow remote entry through man-way openings as small as 0.61m (24") in diameter, after which it expands its locomotors and opens up its collapsible backhoe/manipulator and plow to subsequently perform waste or material handling operations. The design is optimized to meet stringent site and safety requirements, and represents a viable alternative to (i) the long-reach manipulation systems proposed for hazardous storage tank cleanup, and (ii) confined-entry manual cleanup approaches. The system development has been funded to provide waste mobilization and removal solutions for the hazardous waste storage tanks in the Department of Energy (DoE) Fernald and Oak Ridge complexes. Other potential applications areas are the cleanup of heavy-crude petroleum storage tanks. The *Houdini* concept has been submitted to the US Patent Office and a patent has been issued (Patent # pending). We have developed a fully operational prototype which is currently undergoing testing.

I. INTRODUCTION

Environmental restoration of several sites in the DoE's Nuclear Weapons Complex requires remediation of numerous waste storage tanks, such as those at Hanford, Washington, Oak Ridge, Tennessee, and Fernald, Ohio. Due to the hazardous nature of the wastes contained within these tanks, human entry is precluded and the use of remote equipment has been identified as a suitable alternative. Mobile worksystems that would access the tank through existing ports and deploy a variety of tools are viable candidates for in-tank operations, and represent a feasible stand-alone and/or complementary solution alongside the already proposed scenarios of sluicing, and long-reach manipulation.

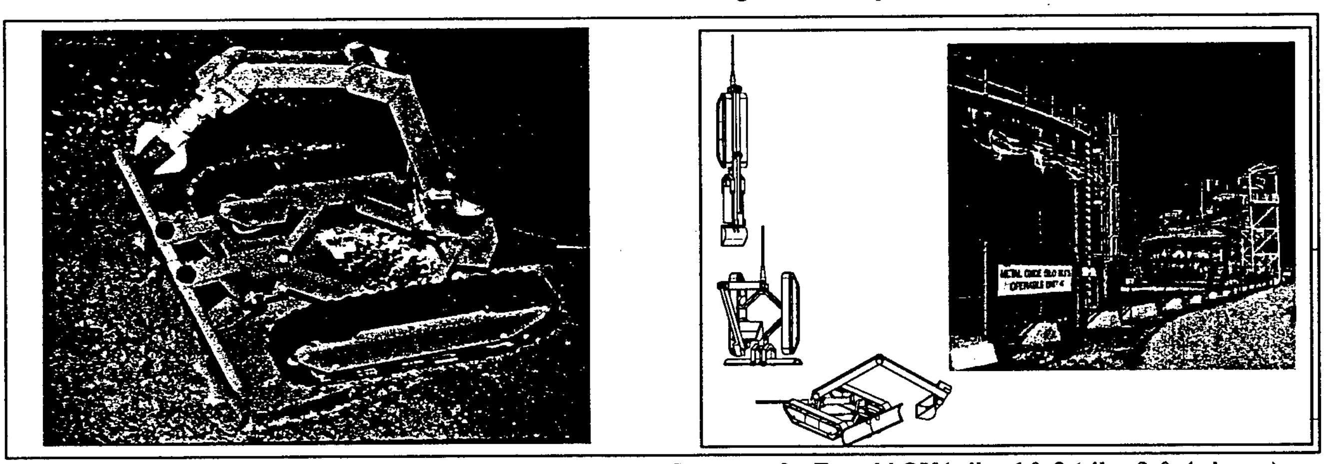

Figure 1: *Houdini* Concept Model and In-Tank Deployment Sequence for Fernald OU4 silos 1& 2 (silos 3 & 4 shown)

DISCLAIMER

II. SYSTEM DESIGN

A. System Configuration

The cleanup of hazardous waste in storage tanks requires the access of robotic equipment through 0.3m (12"), 0.4m (16"), 0.51m (20") or even 1m (42") diameter pipe-risers. The proposed robotic equipment envisioned for this task, shown in Figure 1, is a mobile robot outfitted with the proper sampling and tooling devices, to access the tanks through the different pipe-risers, and once in the tank, fold out and achieve proper working dimensions and configuration. Currently considered tooling encompasses a manipulator/backhoe and a plow. Other solutions would allow for the use of a manipulator with quick-change tooling adaptors.

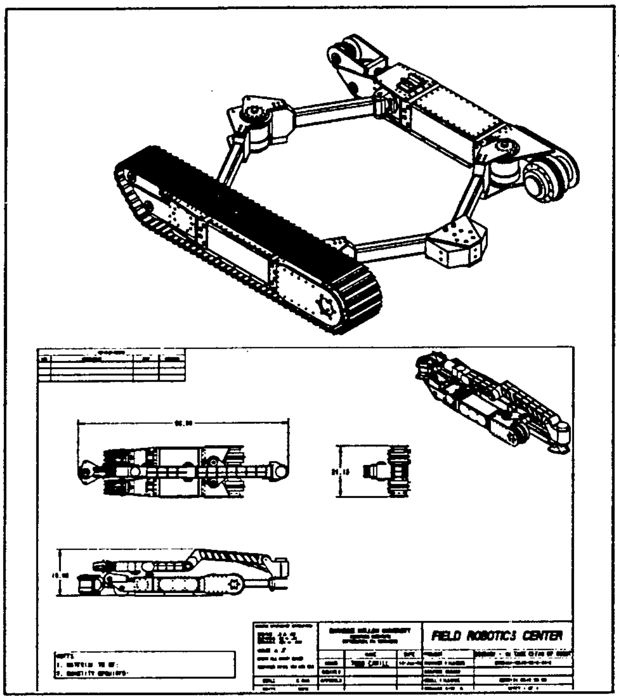

Figure 2: Prototype *Houdini* crawler robot

The robot is to be tethered and teleoperated using cameras on-board the robot and bird's eye views of the entire tank area using one or several cameras deployed through one or several other smaller access pipes [Armstrong et al, 1995]. Such a robot system would eventually operate with a large degree of autonomy, aided by the proper arrangement of sensors, actuation and computational smarts. The robot is lowered into the tank from the deployment pod in its collapsed position via the electro-hydraulic tether, and once in proximity to the ground the frame is actuated to unfold, and the tooling is deployed (backhoe & plow), so that the system can be set onto the ground and begin operations.

The system (shown in Figure 2 with partial treads & without plow-blade/manipulator for clarity) is based on the conceptual design in Figure 1 and has been built and is currently undergoing testing at the Field Robotics Center (FRC) at CMU. We expect to be able to test different exchangeable tread/grouser systems using a conveyor-chain drive, as well as different plow-designs to optimize system performance in different surrogate waste materials.

B. Design Considerations

• Component Layout

Achieving access through the small circular man-ways required the design of a novel active frame-structure to carry locomotors and tooling through the man-way and into the tank. This was achieved through a diamond- or benzene-ring shaped structure with triple rotary hydraulic actuation to open and collapse the frame via remote control (a single rotary actuator/hardstop solution is also possible). Identification of suitable OEM components for the track-locomotor and layout of a collapsible plow (or back-fill blade), as well as packaging of a commercially available hydraulic manipulator system rounded out the preliminary system configuration and design phase. Safety concerns were addressed by providing reliable and redundant actuation systems, low-voltage and explosion-proof servo-valving, inherent spark-proof operation of hydraulics, self-collapse under gravity during extrication, and the use of the tether as an emergency retrieval umbilical.

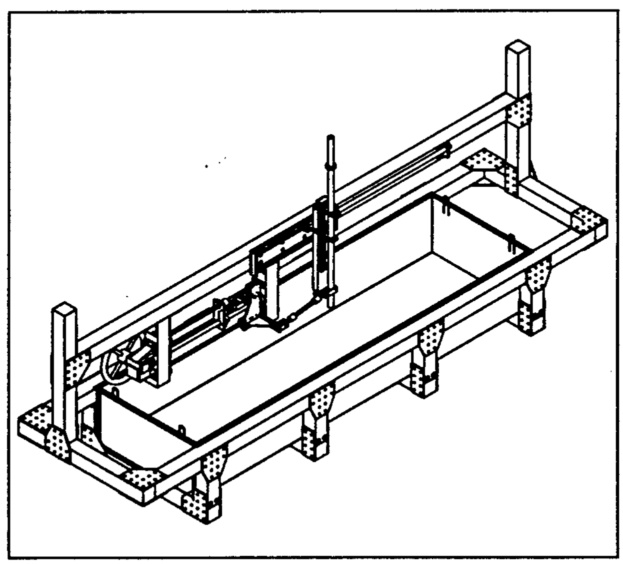

Figure 3: Tread Prototype Test-Stand (Frame, Tank, Instr.)

• Terramechanic Optimization

Mobility on, over, and through the existing tank contents can be insured through proper design of vehicle weight and dimensions, and the development of custom locomotor devices. In order to properly size the track-system, theories and data developed by [Bekker, 1958, 1960, 1969] and experimental data gathered by [Everett et al, 1995] and [Schempf et al., 1995], were used to justify and specify the proper arrangement of locomotor design parameters. A test-pit was designed and built, as shown in Figure 3, which allowed us to use different materials in tanks to test a full or partial tread section using strain-gauges and LVDTs to measure applied loads and displacements to determine sinkage and contact pressure, as well as soil-failure and thus maximum drawbar-pull.

The theoretical comparison and experimental analysis was limited to those soils that most closely resemble those materials bound to be in silos 1 and 2 of The Feed Materials Production Center's OU4 in Fernald, Ohio (FEMCO) [WEMCO RFP, 1991, 1992]. In order to define such parameters as the track-width **b**, the track-height **D**, track-length **l**, grouser depth **h** and the robot weight **W**, use was made of the well-known Bekker-parameters (internal friction angle ϕ, cohesion coefficient **c**, density ρ, deformation moduli $\mathbf{k_c}$ and $\mathbf{k_\phi}$, power ratio **n**, and derived parameters N_c, N_q and $N\gamma$) and their use in several key equations derived by Bekker and listed below.

• Contact Pressure 'P' vs. Sinkage-Depth 'z': (1)

$$P = \left(cN_c + \rho z N_q + \frac{1}{2}\rho b N_\gamma \right)$$

• Sinkage-Depth 'z' vs. vehicle weight and soil parameters: (2)

$$z = \left[\frac{\frac{W}{A}}{\frac{k_c}{b} + k_\phi} \right]^{\frac{1}{n}}$$

• Traction vs.soil shear (A_c), coulomb friction (Wtanϕ) and grouser (H') (3)

$$H = Ac + H' + W\tan\phi$$

• Motion Resistance: R (R_c=compaction > R_b=bulldozing > R_e=entrainment) (4)

$$R_c = 2\left[(n+1)\left(k_c + bk_\phi\right)^{\frac{1}{n}} \right]^{-1} \left[\frac{W}{l}\right]^{\frac{n+1}{n}}$$

• Drawbar-Pull - DP=H-R_c (compaction resistance only) (5)

$$DP = H - R_c$$

One of the important rules-of-thumb was to consider that the track-sinkage should be less than 40% of the track-height, or the tracks would not be able to move through the medium, requiring as large a contact area as possible. Track-width also had to be maximized to reduce sinkage in cohesive materials (loam and clay). In order to increase traction while reducing compaction and bulldozing resistance, the track-length had to be optimized to allow for good traction (in addition to sizing and shaping the grousers) and reduced sinkage, without affecting the turning ability of the robot (expressed as the aspect-ratio of overall length to width, which should remain between 1.0 and 1.8).

In order to make reliable design decisions, geotechnical soils data had to be used, which most closely represents the expected materials to be encountered inside the tanks. Since very little if no data (of the kind we were interested in) was available from inside the tanks, published [Bekker, 1960; Wong, 1989] and experimental data [Schempf, 1991][Everett, 1995] was used to at least bracket the expected system performance of the robot. After several experimental and numerical iterations, the

Vehicle Weight	454 kg (1,000 lb)	20.7kPa (3 psi)	Contact Pressure
Track Width	0.20m (8")	1.1	Aspect Ratio
Track Length	1.22m (48")	5cm (2")	Sinkage Depth
Track Area	0.49m^2 (768in^2)	2,050N (670 lbs.)	Drawbar-Pull
Track Height	0.30m (12")	0.013m (0.5")	Grouser Height
Vehicle Width	1.47m (58in)		

Table 1:HOUDINI Design and Performance Parameters

Houdini system was laid out with the design parameters and the predicted physical performance characteristics shown in Table 1 - experimental verification is currently underway. Based on these specifications a proposed grouser design, shown in Figure 4 has been implemented and is currently under fabrication for experimental verification. Note that we have designed an extruded aluminum backbone around which 60-durometer poly-urea is poured to achieve a self-sealing grouser shape with a 0.5" grouser height attached to a conveyor-chain-link.

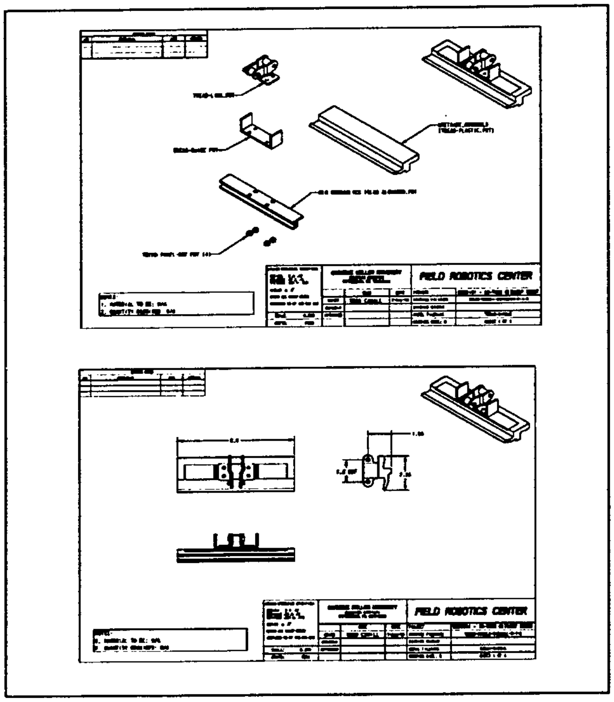

Figure 4: Grouser Prototype Design

III. COMPETING TECHNOLOGIES

There are of course several other commercially available systems which are used to perform in-tank operations. The different approaches known to the author are listed here for completeness sake and as a qualitative illustration of alternative systems and their specialized application niches.

A. Mobile tank-internal spray-gun(s)

The most simple robotic or remote tank-cleanup system consists of a manually emplaced or hydraulically driven folding-frame base spray-gun that is used to spray the insides of the tank with a solvent to make the contents pumpable - the pump is typically a separate unit situated somewhere off along the inside edge of the tank near a manhole.

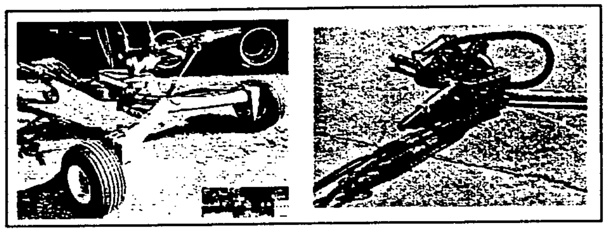

Figure 5: Sludge cannon system from *HBM* and *3I*

The systems shown in Figure 5 clearly show similarities between deployment (foldable frame size for up to 18 inch diameter manway access) and mobility capability (driven wheels vs. fixed supports). These devices, albeit very simple and rugged, require manual assistance to enter/exit and be emplaced, and will only work well with materials that do not need to mixed vigorously (such as by the driving action of treads or augering devices), hence limiting their applicability to certain types of tank contents.

B. Tracked/Wheeled Self-Mobile Auger/ Pump/Skim

There are a few companies that make and lease/ service devices for use in all kinds of above-ground storage tanks. Most of the time the task at hand requires the sluicing for/and removal of the tank contents with one and the same vehicle. Depending on the fluid type, people have used systems that are comprised of snap-together components (tracks, body, gun, hose, etc.) which have to be taken apart, manually reached through the manhole and re-assembled inside the tank before they can be used. Such a system is currently in wide use by LANSCO, Inc. (no picture available). Said device simply uses a set of tracks to move a spray-gun delivering heated diesel fuel to spray down heavy-crude tank residues and then plow them to a point along the periphery of the tank where a pump removes the contents for treatment. Additionally, there is a tank-inspection/cleanup system, based on the Scavenger-robot built by *ARD*, in operation (no picture available).

Another device, originally built by 3I and modified by OCEANEERING, Inc., uses a simple backhoe-skimmer/ auger system to collect in-tank sludges and pump them outside the tank for reclaiming and disposal. The system uses a set of enclosures and explosion-proof lights and cameras to provide a remote operator with a view to allow for completely entryless operation. This device on the other hand needs a much larger manway than other comparable units (for fully assembled access), even if it is broken down into subpieces which have to be manually re-assembled inside the tank.

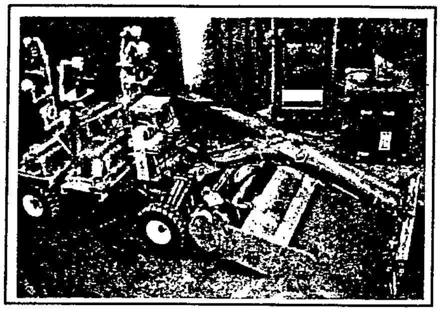

Figure 6: Explosion-proof Sludge-Bug Robot from *Oceaneering, Inc.* with skimmer-backhoe and auger.

A more simpler set of systems, dubbed tracked pumps, simply use a set of dedicated tracks (rubber on steel chain or tread on wheels) with a centrally mounted pump unit to extricate the tank contents (see Figures 7 & 8).

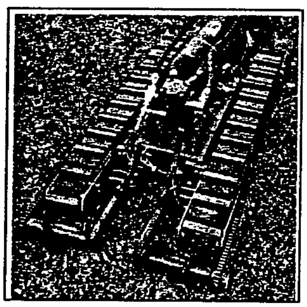

Figure 7: *H&H Pump and Dredge Co.*'s tracked pump

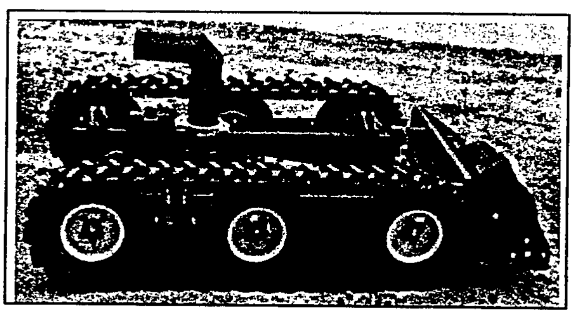

Figure 8: *Liquid Waste Technology*'s system

In either case a frontal (full or partial) auger is used to convey the contents to the pump aided by driving motions. Both systems use either a downward-folding track frame (H&H) or an assembleable/actuated in-line hinged frame design (LWT) to allow the system to enter a tank through a 0.61m (24in.) diameter manway.

C. Patented Mechanisms

Of course there are a variety of currently existing methods to expand and contract frames to which track mechanisms can be attached. Such devices can range from directly perpendicular linear extension mechanisms (US Pat.#3,712,398 & 3,820,616), to collapsible parallelogram configurations (US Pat.#3,700,115), to even dual triangular frame members (USSR Pat.#K9875A/50*SU-591-349).

IV. CONCLUSIONS

Based on the above design and performance numbers it seems reasonable to conclude that the track-driven *Houdini* robot system will be able to locomote on the expected silo wastes (contact pressure of 21 kPa is well below the allowable bearing capacity of all considered soils), with a minimum of sinkage (5cm = <15% of track-height), be extremely maneuverable (length/width aspect ratio = 1.1), and with a pull-to-weight ratio of 0.67. In other words it seems entirely feasible to utilize up to 67% of the vehicle's dead weight to plow material, which would translate into a volume of 0.06m^3 (2ft^3) of material that could be moved on each plowing run (according to density figures shown in Table 1). Based on average speed figures of 3.2 to 4.8 kph (2 to 3mph), the material removal rate of this system is extremely high; much larger than current payloads of similarly-sized industrial manipulators and yet comparable to those of small excavators from Nissan and Kobelco. Note also that the ratio of manipulator-payload to vehicle-weight is also substantial (200/1,000 = 0.2), allowing for pick-and-place operations of a wide variety of unexpected solid-waste objects that may be found within the waste material for extrication via a separate tram-bucket.

The validity of the above analysis is based on the geotechnical soil parameters of 'bounding' soil types and compositions, as well as moisture content and plasticity. Before the final system is detailed and fabricated, theoretical and experimental analyses will be repeated based on actual soil-data from the waste-silos (if available), or synthetic waste material (non-radioactive) provided by the facility to be cleaned up.

V. SUMMARY

The design of a new in-tank mobile cleanup system to allow for remote entry through constrained manways has been proposed and the critical design and performance parameters specified. Commercially available mobile systems for material handling tasks are not suited for this type of application due to their inherent size and performance characteristics. The *Houdini* system is well suited for a wide variety of cleanup tasks ranging form petroleum storage tanks to hazardous waste containment tanks, due to its modular design, allowing the exchange of locomotors and tooling, while accommodating a wide variety of access-manway sizes.

VI. ACKNOWLEDGEMENTS

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