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Houdini: In-Tank Mobile Cleanup Robot

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Abstract

This paper describes design and analysis efforts to develop a new reconfigurable and collapsible working machine, dubbed *Houdini*, 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 0.51m (20") in diameter, after which it expands its locomotors and opens up its collapsible backhoe/manipulator and plow to subsequently perform waste or product handling operations. The design is optimized to meet stringent site and safety requirements, and represents a viable alternative to the long-reach manipulation systems proposed for hazardous storage tank cleanup. The design analysis was performed on key design parameters such as track-width and -length, vehicle weight and aspect ratio, to insure that the system will be able to be supported and locomote over/through a wide range of amorphous/solid materials. Theoretical and experimental analyses using the Bekker-parameters are presented to support these findings. The system has currently been proposed as an alternative to provide waste mobilization and removal solutions for hazardous waste storage tanks in the Department of Energy (DoE) complex, and we are currently teamed with two major aerospace and robotics companies, trying to obtain funding to develop an operational prototype system for the DoE. Other potential applications areas are the cleanup of heavy-crude petroleum storage tanks for American Petroleum Institute (API) inspection tasks and Environmental Protection Agency (EPA) required cleanup and/or decommissioning activities.

Introduction

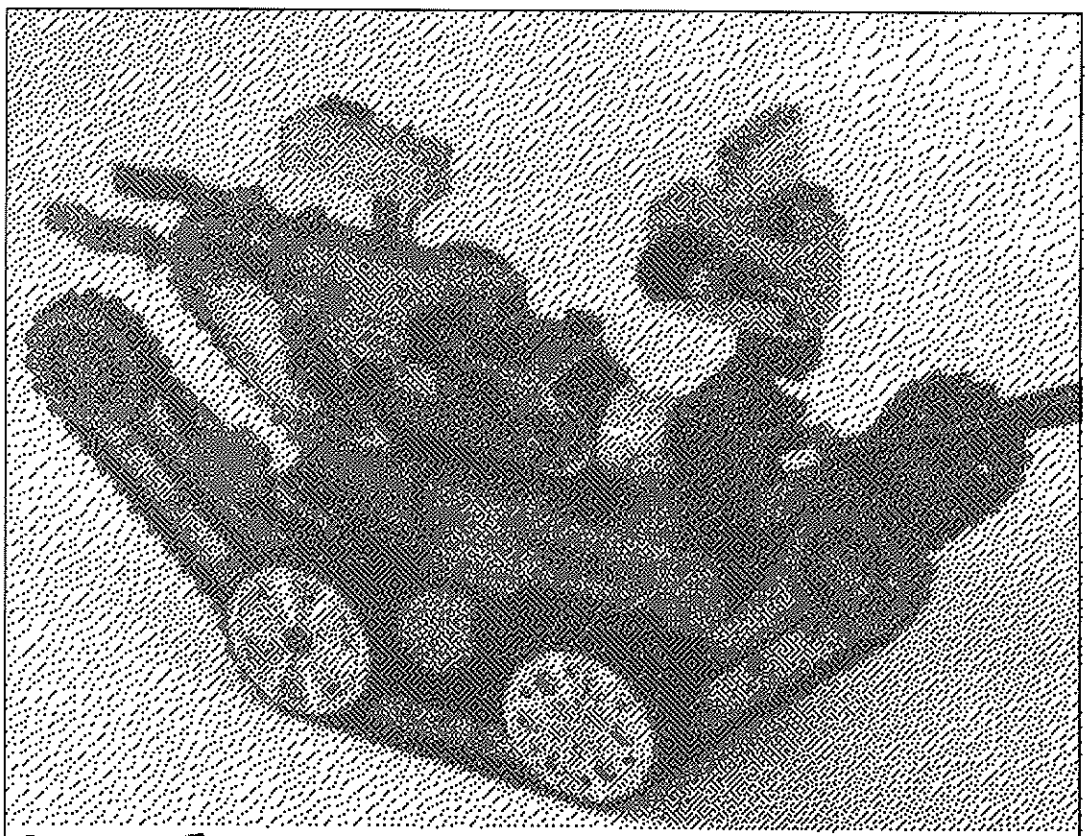
Environmental restoration of several sites in the DoE's Nuclear Weapons Complex requires remediation of numerous waste storage tanks, such as those at Hanford, Washington, and Fernald, Ohio. Due to the hazardous nature of the wastes contained within these tanks, human entry is precluded and the use of remote equipment has been identified as a suitable alternative. Mobile worksystems that would access

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the tank through existing ports and deploy a variety of tools are viable candidates for in-tank operations, and represent a feasible stand-alone an/or complementary solution alongside the already proposed scenarios of sluicing, and long-reach manipulation.

A typical mobile worksystem consists of several types of tooling devices mounted on a single self-mobile platform, thus offering the versatility needed to handle multiple waste forms. Mobile worksystems can travel on, over, and through materials ranging in consistency from concrete to pitchblende to sludge, allowing proven material handling tools and techniques to be used on the tanks' contents. The inherent system simplicity, as demonstrated in numerous instances of construction equipment, make mobile worksystems reliable, easy to maintain and operate. Multiple such worksystems could be lowered into a waste tank through several access ports, and work in concert. Few systems can beat the collective productivity of several excavator/bulldozer systems for moving massive quantities of diffuse materials, but none of those systems is as suited for the in-tank waste handling and removal task as the mobile robot proposed in this document.

Mobile platforms which come closest in size and capability to the material removal and performance requirements are those available from Kobelco [Kobelco, 1993], and Remotec, Inc. [Remotec, 1992]. The respective systems are shown in Figure 1 and Figure 2:



Remotec ANDROS Mark VI

Figure 1: Commercially available 'miniature' mobile worksystems

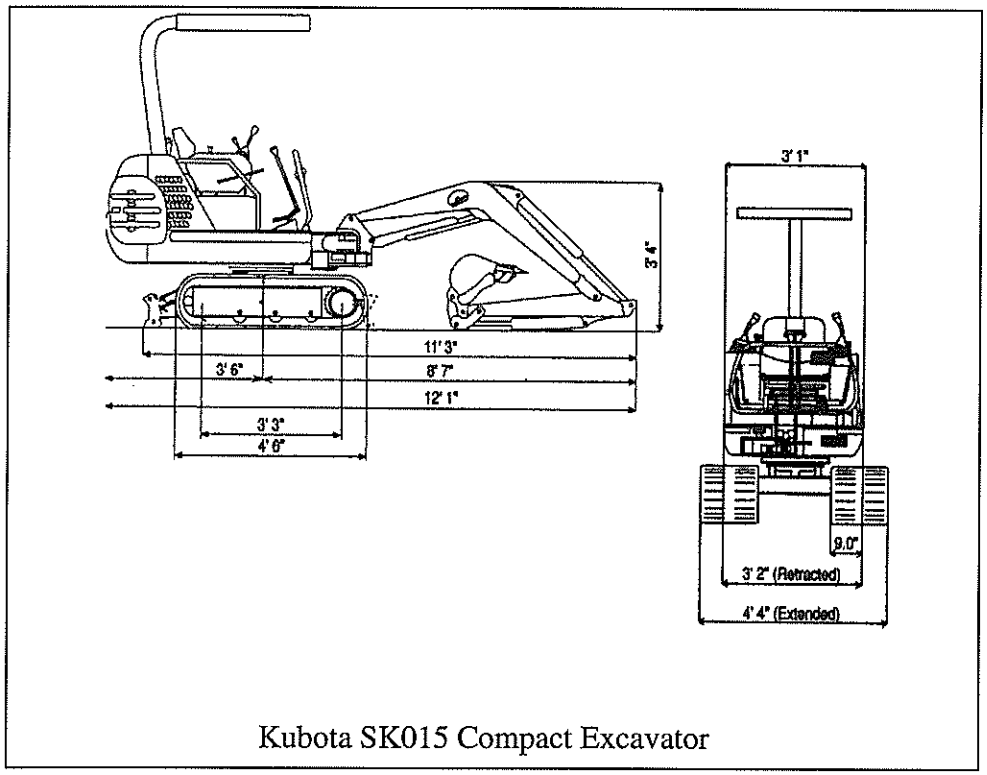


Figure 2: Commercially available 'miniature' mobile worksystems

The man-operated system from Kobelco is not really sized for access through small circular man-ways, and would have to be completely re-designed, especially as its weight (due to the on-board diesel engine) is excessive. The remotely operated ANDORS Mark VI system from Remotec, Inc. could fit through the access-port with some modifications, but it is believed that for reasons of maneuverability, sinkage, and reduced payload capacity it does not necessarily represent the most appropriate system solution. It has been used in the spray-cleanup of a storage tank, but the tank-opening was much larger, the tank was completely empty and the floor had been cleaned down to the bare metal.

Design and analysis efforts to develop a new "transformer-like" collapsible working machine, dubbed *Houdini*, to remotely clean up hazardous-waste and petroleum storage tanks are the focus of this paper. The tethered robot system is designed to allow remote entry through man-way openings as small as 0.51m (20") in diameter, after which it expands its locomotors and opens up its collapsible backhoe/manipulator and plow to subsequently perform waste or product handling operations. The design is optimized to meet stringent site and safety requirements, and represents a viable alternative to the long-reach manipulation systems proposed for hazardous storage tank cleanup. The new *Houdini* system, being a custom-designed solution, allows for the optimization of all key design parameters such as variable aspect-ratio, high-capacity and interchangeable tooling, multiple locomotion modes and low contact pressure, sinkage and high waste handling capacities. The benefits of the *Houdini* system are the combination of its relatively low cost, short development time, low

infrastructure and logistical requirements. Furthermore, little or no facility modifications are required. The system can be built to be rugged and reliable, including inherent operator, process, and environmental safety features. The system also distinguishes itself by its tooling and sensing type and versatility, and high material handling rates compared with any other currently proposed remotely operated waste removal device. Multiple robot systems could simultaneously remediate one or several tanks faster than any large single dedicated system. Alternate uses as exploratory camera/lighting and support tooling platform and material feeder for large scale manipulator systems are also possible uses for such an in-tank mobile base.

Reducing infrastructure support and logistics for any such cleanup task will provide the DoE and the nation with a faster and cheaper cleanup program, no matter which cleanup solution is chosen. Safety to site operators, the environment, and the public at large can be maximized if no facility modifications are required, such as cutting tanks open and having to build large air-lock domes with controlled atmospheres and air-locks. Reducing the amount of hardware needed to clean up these tanks, will also reduce the amount of material to be decontaminated or disposed of after the task is completed. The development time and cost of a simple yet capable robotic system should always be an important criteria to be considered when conceiving and proposing a system, and while evaluating different alternative solutions. Initial estimates indicate that the in-tank mobile robot *Houdini* should be at least an order of magnitude cheaper to produce in quantity, and will be available for testing, evaluation, demonstration and deployment in a much shorter time-frame than any other long-reach robotic manipulator systems.

System Design

- ***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 3, 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 or backhoe. Other solutions would allow for the use of a manipulator with quick-change tooling adaptors. The design candidates are to be seen as a general class of compact and collapsible devices, whose dimensions can be made to fit almost any diameter access pipe - with theoretical limits on the low end set purely by componentry size.

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. Such a robot system would eventually operate with a large degree of autonomy, aided by the proper arrangement of sensors, actuation and computational smarts.

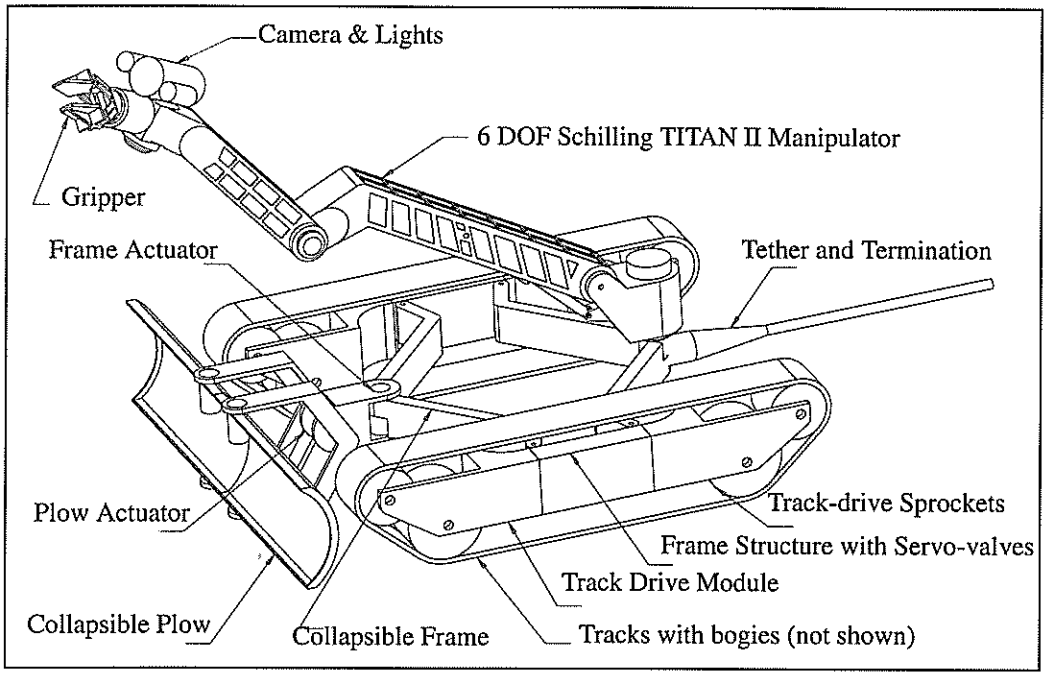


Figure 3: Configuration of the *Houdini* robot system (shown here with a Schilling TITAN II manipulator)

The deployment sequence for the *Houdini* system is shown in Figure 4, where a deployment-pod containing the robot is shown mated to the tank via a support structure, and the three main steps of deployment are illustrated. The robot is lowered into the tank via the hydraulic tether, and once in proximity to the ground the frame is actuated to open up, and the tooling (shown here as a back-hoe and plow) is unfolded, so that the system can be set onto the ground and begin operations. Since the robot is tethered and hydraulically powered, a tether management system will remain atop the tank and lower the robot into the tank, feed additional tether as the robot moves around inside the tank, and retrieve the robot out of the tank for storage, maintenance, tooling exchange, or emergency retrievals. Tools which are currently envisioned consist of a collapsible backhoe and frontal plow (also termed a back-fill blade). These tooling systems represent essential and efficient material handling and haulage devices for large bulk material movement. Precedence for such systems is apparent in the current configuration of most industrial construction equipment. On-board and bird's-eye-view cameras inserted through other risers will allow the operator located at a remote console to control and oversee the working performance of the robot at all times. Add-on tooling for the robot such as waterjets, scouring grinders, and long-reach dexterous booms are all envisioned for subsequent decommissioning tasks. The system has been mocked up and commercial components identified which would allow for a rapid full-scale prototyping activity and demonstration in a realistic environment.

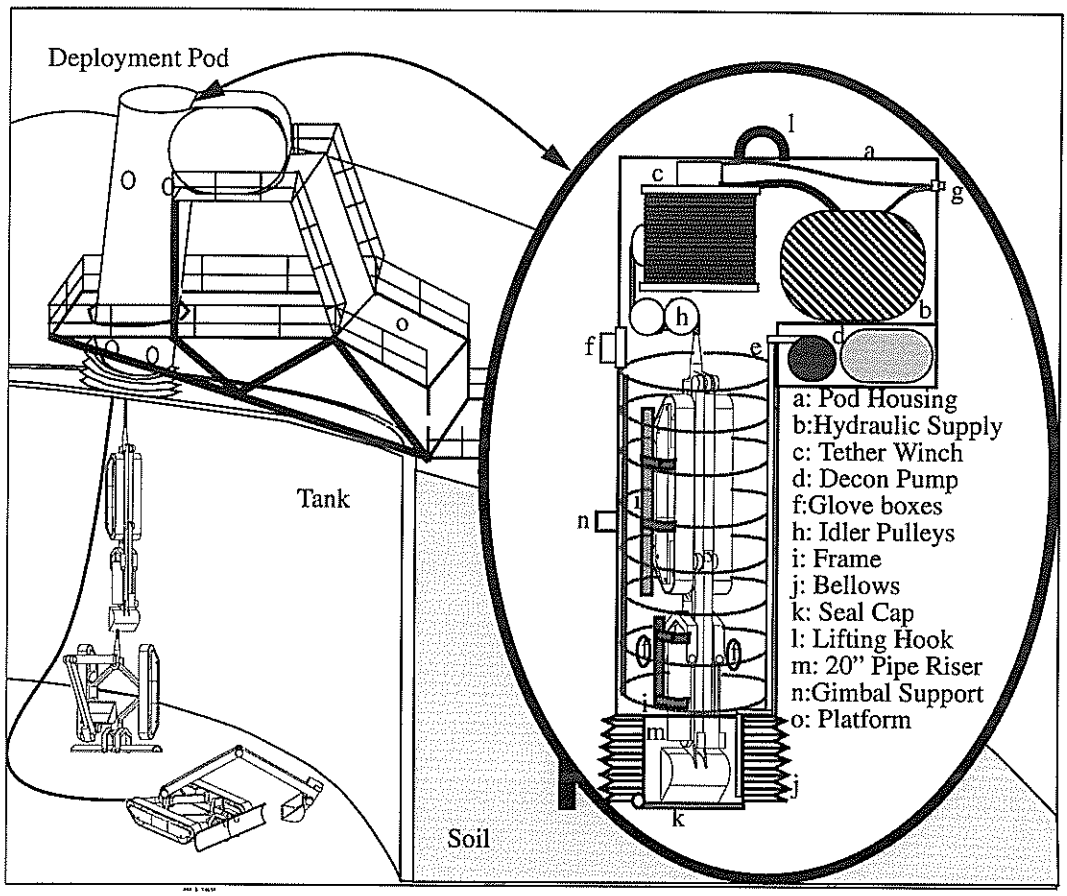


Figure 4: Deployment sequence of the *Houdini* system

- ***Design Considerations***

1. 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 dual rotary hydraulic actuation to open and collapse the frame via remote control. 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, yielding the design as shown in Figure 3. 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 device. The most appropriate tooling needed to move the hazardous materials is initially envisioned to be a backhoe and a plow (backfill blade), or possibly a manipulator with a quick-change end-effector. The utility of these tools on a mobile base has

been proven to be the most effective and efficient means to move and handle materials of varying consistencies. Even though the baseline system is proposed with track-driven locomotor, it is entirely feasible to replace these with 4 separate auger-drives should flotation and traction requirements change within a tank or from tank to tank. The ability to exchange not only locomotors, but tooling devices, makes this system extremely versatile and an appropriate solution for cleanup of varying environments.

2. 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 [Schempf, 1991], were used to justify and specify the proper arrangement of locomotor design parameters. The 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 $\mathbf{N_c}$, $\mathbf{N_q}$ and $\mathbf{N\gamma}$) and their use in several key equations derived by Bekker and shown 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 ($W\tan\phi$) and grouser (H') (3)

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

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

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

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] was used to at least bracket the expected system performance of the robot. Typical soil parameters as proposed by [Bekker 1958, 1960, 1969] are tabulated below:

Table 1: Geotechnical Soil Parameters

	Sandy Loam	**Clayey Soil**	**Wet Sand**	**Silo 1 & 2 Waste**	**Bento Grout**
Moisture (%)	>100%	55%	15%	22% - 78%	40%
c [lb/in^2]	1.6	0.5	0.15	?	4.23
ϕ [deg]	15	11	29	?	8
n	0.4	1.0	0.7	?	1.67
$\mathbf{k_c}$ [lb/in]	0.8	7	2.3	?	40
$\mathbf{k_\phi}$ [lb/in^2]	1.4	5	16.8	?	4.25
$\mathbf{N_c}$	14	10	37	?	8
$\mathbf{N_\gamma}$	3	1	19	?	0.5
$\mathbf{N_q}$	5	3	19	?	2
ρ [lb/in^3]	0.7172	0.05775	0.04746	0.0926 to 0.1215	0.03183 to 0.0411

After several experimental and numerical iterations, the *Houdini* system was laid out with the following design parameters (left), and the resulting physical performance characteristics (right):

Table 2:*Houdini* Design and Performance Parameters

Vehicle Weight	318 kg (700 lb.)	8.97kPa (1.3 psi)	Contact Pressure
Track Width	0.14m (5.5")	1	Aspect Ratio
Track Length	1.22m (48")	2cm (0.7")	Sinkage Depth
Track Area	$0.34m^2$ ($528in^2$)	2,050N (460 lbs.)	Drawbar-Pull
Track Height	0.33m (13")		
Vehicle Width	1.22m (48in)		
Grouser Height	0.025m (1")		
Grouser Height	0.025m (1")		

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 9 kPa is well below the allowable bearing capacity of all considered soils), with a minimum of sinkage (2cm = <10% of track-height), be extremely maneuverable (length/width aspect ratio = 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 (200/500 = 0.4), allowing for pick-and-place operations of a wide variety of unexpected solid-waste objects that may be found within the waste material.

The validity of the above analysis is based on the geotechnical soil parameters of 'bounding' soil types and compositions, based on moisture content and plasticity. Before the actual system is detailed and fabricated, theoretical and experimental analyses would 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.

Summary

The design of a new in-tank mobile cleanup system to allow for remote entry through constrained man-ways has been proposed and the critical design and perfor-

mance 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 it modular design, allowing the exchange of locomotors and tooling, while accommodating a wide variety of access-man-way sizes. We hope to receive funding from the DOE to develop a fully operational prototype for demonstration in 1994.

Acknowledgments

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