those indicating a freeway entrance, are often much lower, down to around 0.6 m (2 ft). Thus, the marginally acceptable range for this metric would be 0.6-3.6 m (2-12 ft), with the ideal value being a little higher at 0.6-4.3 m (2-14 ft).

2.3.5. Mass of Tool

The National Institute for Occupational Safety and Health (NIOSH) devised an equation to determine the recommended maximum weight that can be lifted by a worker under certain predetermined conditions. Because these limits are dependent upon the geometry and location of the item being lifted, and the form and location of the tool is currently undefined, these values are taken to be rough approximations only, and will need to be more closely defined as the design progresses. However, if the tool is to be lifted manually be a single worker, it would need to be light enough and small enough to do so, so for the following calculations the form of the tool is assumed to be a large backpack.

The NIOSH Lifting Equation is

$$\mathrm{RWL} = \mathrm{LC} \times \mathrm{HM} \times \mathrm{VM} \times \mathrm{DM} \times \mathrm{AM} \times \mathrm{FM} \times \mathrm{CM} \tag{2.1}$$

where

- RWL = Recommended Weight Limit
- LC = Load constant, 23 kg
- HM = Horizontal Multiplier, 25/H, where H is the distance between the worker and the center of mass (CM) of the item
- VM = Vertical Multiplier, 1 - (0.003 |V - 75|), where V is the vertical height of the item from which it is lifted
- DM = Distance Multiplier, 0.82 + (4.5/D), where D is the vertical travel distance through which the item is lifted

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- AM = Asymmetric Multiplier, 1-(0.0032A), where A is the angle between the asymmetry line and the mid-sagittal line. This is basically a measure of how much a worker must twist when picking up the item. Figure 2-1 shows how this angle is determined.
- FM = Frequency Multiplier, derived from the frequency and duration of the lifting. Because the tool is assumed to be lifted infrequently (<0.2 lifts/min) and for a short duration (<1 hour), this multiplier is set at 1.
- CM = Coupling Multiplier, derived from the quality of had-to-item coupling, or how easy it is to grasp the object. This multiplier will be set at 1, since it is assumed that the tool will be designed such that it is easy to lift (e.g. using straps or handles)

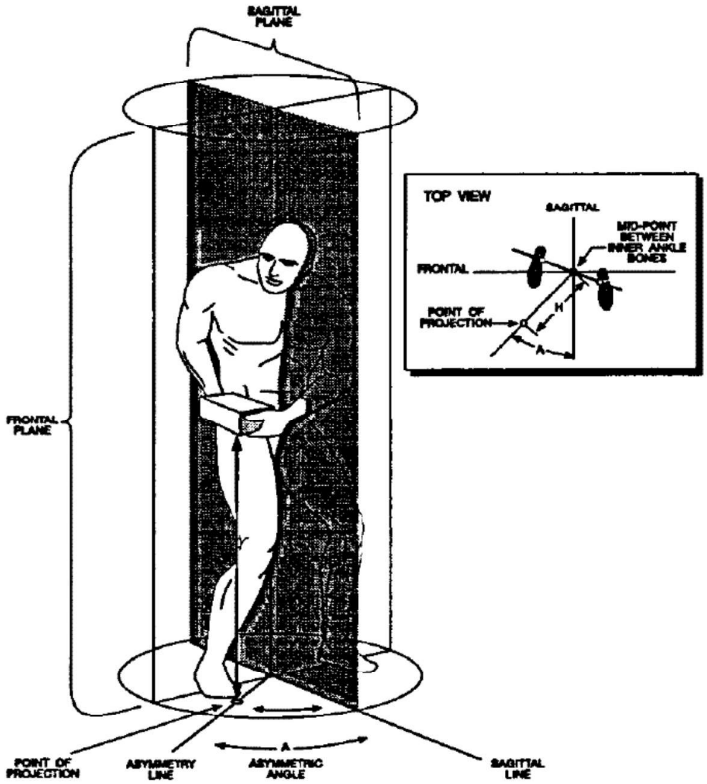

Figure 2-1: Determination of asymmetry angle [25]

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Assuming that

- The tool is lifted from a height of 45 cm (location of straps/handles)
- The CM is located 30 cm away from the worker
- The tool is lifted to a height of 110 cm (roughly the height at which a backpack is worn), the distance of lift is 65 cm
- The worker can position himself in front of the tool such that the asymmetry angle is minimized to no more than 15°

then the lifting equation returns an RWL of 14.8 kg (32.6 lbm). This would be the marginally acceptable value for this metric, with an ideal metric being less than three quarters of this value, or 11 kg (24.3 lbm).

2.3.6. Noise Produced by Tool

Table 2-5 shows permissible noise exposures taken from OSHA regulations above which hearing protection must be worn. In order to keep usage of the tool as simple as possible, it is desirable that the worker not need hearing protection during operation. A worst-case scenario would have the worker cleaning graffiti for a maximum of six hours in a day, which would indicate a marginally acceptable value for this metric to be less than 92 dBA.

Duration per day (hours)	Sound Level (dBA, slow response)
8	90
6	92
4	95
3	97
2	100
1.5	102
1	105
0.5	110
0.25	115

Table 2-5: Permissible noise level exposures [26]

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A more ideal value would be less than that of the actual noise level of the freeway, which at 10 meters is between 75-80 dBA [27], so the ideal value of this metric will be set at 75 dBA.

2.3.7. Time of Direct Contact with Chemicals

"Direct contact" will be defined as exposure to the possibility of bodily contact with the chemical, as well as exposure to chemical vapors or fumes. Despite most graffiti removal chemicals being formulated to be as non-toxic as possible, limiting the amount of exposure to the chemical to the minimum amount of time is desirable. Currently, the worker uses a rag to apply the chemical to the sign, resulting in a large time of direct contact. The marginally acceptable value for this metric would be exposure times slightly less than that of the current method, which would be around 120 seconds per cleaning until the chemical container is emptied. This total time is dependent on the amount of chemical used per cleaning as well as the size of the container, but is likely larger than 600 seconds (or 5 cleanings). Thus, the marginally acceptable metric will be 600 seconds. An ideal situation would be no contact at all apart from loading cleaner into the tool, which should take no more than a couple of minutes. Thus, the ideal value for this metric would be less than 120 seconds.

2.3.8. Radius of Turn

If the sign to be cleaned is a few meters away on the side of the road, the worker will take the tool out to the sign, clean it, then turn around and head back to the vehicle. This metric describes the area necessary to completely turn the tool around and move in the opposite direction of travel. Because the vegetation on roadsides can be somewhat dense, a marginally acceptable value for this metric would be one meter (3.3 ft). An ideal value

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for this metric would be zero meters (zero feet), meaning that the tool can be turned around in place.

2.3.9. Rate Over Rough Terrain

The average walking speed over rough terrain is 1.3 m/s (4.3 ft/s) [28]. The ideal value for this metric would be equal to that, while a marginally acceptable value would be half that, or 0.65 m/s (2.1 ft/s).

2.3.10. Time to Learn How to Use Tool

It is important that the use of the tool be as intuitive as possible, although some instruction will most likely be needed. Thus, a marginally acceptable value for the time it takes to learn to use the tool, including consumable part replacement, adding cleaner, and tool operation, should be no more than ten minutes, or 600 seconds. An ideal value for this metric would be less than five minutes, or 300 seconds.

2.3.11. Area of End Effector

The value of this metric will depend on the geometry of the end effector. The tool should be able to be used to clean smaller signs, and to spot clean on larger signs. However, if a large area of graffiti needs to be cleaned, then the end effector should be large enough that it does not take a long time to do so. Most of the signs to be cleaned are no less than 0.3 m (12 in) on their smallest side [29], so the length of a side of the end effector should be no larger than this. Thus, if the geometry is square, the area would be 0.09 m^2 (139.5 in^2); if an equilateral triangle, 0.04 m^2 (62.0 in^2). A circular geometry is not feasible since it would not be able to effectively clean the corners of the sign. However, many signs are larger than these described, so the end effector may be larger, closer to 0.46 m (18 in) per side. However, this may mean that the smaller signs will need

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to be cleaned by some other method, which reduces the usefulness of the tool. Thus, a marginally acceptable range for this metric would be between 0.19-0.20 m^2 (294.5-310.0 in^2), with an ideal value of 0.04-0.09 m^2 (62.0-139.5 in^2).

2.3.12. Compatibility of Cleaner and Materials

This is a subjective metric, but the materials of the tool that come into contact with the cleaning fluid should be chosen to be as non-reactive as possible to avoid corrosion, leaking or other damage to the tool.

2.3.13. Dimensions of Tool

The tool should be able to fit into a service vehicle to be taken out into the field. The bed dimensions for a standard bed Chevrolet Silverado, which is a common vehicle used by maintenance departments, are 2.5m (97.8 in) long by 1.6 m (64.7 in) wide by 0.6 m (24 in) deep. Thus, these are the marginally acceptable values for this metric. However, keeping in mind that a goal for the tool is that it must be able to be lifted by the worker, the ideal dimensions for the tool are much less, and will be less than 1 m (3.3 ft) per side. The wand portion may be longer, but should be shorter than 2.5 m (8.2 ft) when stored, so that it fits into the bed of the truck without sticking out.

2.3.14. Time to Disassemble

This metric represents the total time it would take to disassemble the tool for cleaning or servicing, and is highly dependent on the features, geometry, materials and other characteristics of the tool. As such, it may need to be further refined later in the design process. However, it should not take a worker an inordinate amount of time to service the tool, whether it is cleaning or replacing parts, and the most frequently replaced parts should be easy to service. Thus, a marginally acceptable value for this metric would be

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one hour, or 3600 seconds, to completely disassemble the tool for servicing, with an ideal value being less than 900 seconds.

2.3.15. Operating Time Between Maintenance Cycles

The tool should be designed in such a way that maintenance needs such as cleaning or part replacement, other than consumable parts or cleaning fluid refills, are as infrequent as possible. An acceptable value would be one maintenance cycle for two month's worth of daily use, or 480 hours. An ideal value would be greater than twice this, or over 960 hours.

2.3.16. Cost of Tool

In order to make the tool attractive to potential buyers, its cost should be kept as low as possible. This may be achieved in part by keeping the cost of its parts as low as possible, which can be done by using off-the-shelf components for motors, pumps, tanks, etc. While more marketing research should be done in order to determine a completely accurate price point, it would seem that a cost of $1500 for the tool would be marginally acceptable, while a cost of less than $1000 would be ideal.

2.3.17. Force Applied to End Effector

In order to make the use of the tool as effortless as possible, the amount of force necessary both to clean the sign and move the end effector around on the face of the sign should be minimized. Since the cleaning fluid must be recovered, it is likely that most or all of the axial force applied to the sign may come from a vacuum system which will suck the end effector onto the face of the sign. However, this may make the end effector difficult to move parallel to the face, so the axial force must be balanced with the force required to do this. A comprehensive literature search on the ergonomics and

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biomechanics associated with the particular configuration of the sign cleaning tool (i.e. finding the required force to move a mass on the end of a pole across a vertical plane) was fruitless. Any literature available suggested that the configuration be altered, which in this case is not possible. However, testing on the end effector (as explained later in the report) used a maximum axial force of 37.8 N (8.5 lbf), which seemed to effectively clean the surface of the sign. Therefore, pending further ergonomic tests with the sign cleaning tool (or an effective model), both the marginally acceptable and ideal values for this metric will be set at 37.8 N.

2.3.18. Ratio of Volume of Chemical Applied to Chemical Recovered

In order to maintain the retroreflective level of the sign, and to prevent chemicals from entering the environment in violation of National Pollutant Discharge Elimination System (NPDES) regulations, it is important that every effort be made to remove and capture the cleaner that is applied to the sign. Allowing for evaporation, a marginally acceptable value for this metric would be 90%, while an ideal value would be greater than 95%.

2.3.19. Tool Applies Scrubbing Motion

This is a subjective metric, but the tool should emulate the back-and-forth motion a worker uses to clean the sign, because it exposes the paint to oscillating shear forces that will help break the chemical bonds and remove the paint faster.

2.3.20. Sign Cleaner Checks Retroreflectivity After Cleaning

This is a binary metric. In order to check the retroreflectivity of the sign, a retroreflectometer must be integrated into the tool, most likely on the end effector. Due to the expense and size of this type of equipment, which arises from sensitive electronics,

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traceable calibrations and the necessary geometry of the meter, this may at the very least affect the price point significantly, and probably other metrics as well.

2.4. Candidate Designs

There is a wide array of choices for the design of the sign cleaner, so it is helpful to break the system up into smaller chunks to be integrated at the end. Essentially the parts of the sign cleaner are:

- The power source
- The form of the main equipment
- The form of the wand
- Cleaning fluid delivery
- Cleaning fluid recovery and disposal
- The form of the end effector
- Method of ensuring that sign is not damaged

The following sections will examine possibilities for each of these system parts and will discuss pros and cons of each.

2.4.1. Power Source

This section outlines the options for the source of the power for the sign cleaning tool. Four options are considered: a portable battery, a portable gasoline engine, a stationary gasoline engine, and a plug on the vehicle.

2.4.1.1. Portable Battery

This option uses a portable rechargeable battery for the power source, meaning one that is light enough to comfortably carry around yet has enough power to perform the required tasks. It would most likely be nickel-metal hydride or lithium-ion because these

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are the most readily available and power-dense types of batteries, and if possible it should be a common commercial off-the-shelf battery.

Pros of battery use include:

- Unlimited range of travel with the tool, in terms of being tethered to anything
- Less pollution
- Good energy density
- Easily replaced
- Quiet operation
- High probability that shop has compatible charger, especially if the battery geometry is identical to that used in common battery-powered tools

Cons of battery use include:

- Weight, depending on how many are needed
- Up-front cost
- Will need to be replaced eventually
- May need more than one set, depending on discharge rate and capacity

2.4.1.2. Portable Gasoline Engine

This option uses a portable gasoline-powered engine for a power source, much like that on a leaf blower. There are two different ways to use the power: using a power take-off (PTO) point, and making the entire design mechanical; or using the engine to generate electricity, and making the design electromechanical. Both have their drawbacks: a PTO would require that power be transferred all the way from the user to the face of the sign, which would be a complex endeavor at best; and power conversion to electricity is lossy, more so if the electricity is used later to run a motor.

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Pros of portable gas engine use include:

- Good energy density
- Common parts and tools for maintenance and repair
- Familiarity of use
- No need to recharge or replace

Cons of portable gas engine use include:

- Heavy
- Requires more maintenance
- Pollution
- Noisy operation
- May require multiple power conversions

2.4.1.3. Stationary Gasoline Engine

This option is similar to the portable gasoline engine, except it would remain on the service vehicle. It would also most likely allow all other equipment except for the wand and cleaning head to remain on the vehicle

Pros of stationary gas engine use include:

- Power is easily sufficient
- Common parts and tools for maintenance and repair
- Familiarity of use
- No need to recharge or replace
- Reduced tool mass held by user
- Noise is distant from user

Cons of stationary gas engine use include:

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- Limits range, user is tethered to vehicle
- Heavy to load in and out of vehicle
- Requires more maintenance
- Pollution
- Noisy operation
- May require multiple power conversions

2.4.1.4. Plug on Vehicle

This option uses the service vehicle as the power source. This could be as simple as a plug to provide power, or as complex as having all equipment except for the wand and cleaning head on the vehicle.

Pros of using a plug on the vehicle include:

- Reduced tool mass
- No need to develop new power source
- Power is easily sufficient
- Noise is distant from user

Cons of using a plug on the vehicle include:

- Limits range, user is tethered to vehicle
- Requires vehicle modification
- Limits which vehicle may be used

2.4.2. Form of Equipment

This section outlines the form that the equipment would take, excluding the wand and end effector. Four forms are explored: handheld, backpack, dolly and vehicle-mounted.

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2.4.2.1. Handheld

This option would enclose everything into a small handheld tool, roughly the size and form of a handheld steam or vacuum cleaner, or possibly a leaf blower. Whether or not the tool would fit into this form is highly dependent on its power requirements, necessary fluid capacities, mass of components and other characteristics. However, it would be highly desirable due to its small form.

Pros of a handheld sign cleaner include:

- Lighter
- Smaller
- Highly maneuverable
- Not tethered to vehicle
- Lower cost

Cons of a handheld sign cleaner include:

- Less fluid capacity
- Less battery capacity
- Requires arm strength to hold, may be fatiguing

2.4.2.2. Backpack

This option would have all equipment mounted on a backpack chassis, much like a backpack leaf blower. This retains the freedom of movement of the handheld form, while allowing an increase in power and fluid capacity.

Pros of a backpack form include:

- Larger fluid capacity
- More power available (larger batteries, gas engine)
- Very maneuverable

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- Not tethered to vehicle

Cons of a backpack form include:

- Heavier to lift and carry
- Possible noise issues from equipment located close to user's head

2.4.2.3. Dolly

This option would have all equipment mounted on a rolling chassis that the user would pull behind himself. This allows the capacities and equipment to be larger, but reduces maneuverability.

Pros of a dolly-mounted system include:

- Larger fluid capacity
- More power available
- Less fatigue to user, due to holding only hoses and wand

Cons of a dolly-mounted system include:

- Heavier
- Difficult to maneuver over rough terrain
- Difficult to reach remote spots, such as hillsides

2.4.2.4. Vehicle Mounted

For this option all equipment, except hoses and wand, would be mounted (not necessarily permanently) to the service vehicle. This allows the user to move only the hoses and wand, greatly reducing fatigue, while increasing power and capacity significantly.

Pros of a vehicle-mounted system include:

- Largest fluid capacity

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- Power is easily sufficient
- Less fatigue due to only holding hoses and wand

Cons of a vehicle-mounted system include:

- Limited range (tethered to vehicle)
- Cleaner must be loaded and unloaded, or requires dedicated vehicle
- Heavy

2.4.3. Form of Wand

This section outlines the possible form that the wand would take, which is the part of the tool that the operator uses to place the end effector on the sign. Three forms are examined: static, sections and telescoping.

2.4.3.1. Static

This wand form would be a simple member of inalterable length.

Pros of a static wand include:

- Light
- Very simple design and construction
- Easy to integrate fluid/power paths
- Inexpensive

Cons of a static wand include:

- Reach is limited by length
- Difficult to reach low, high areas
- Length may make it difficult to store

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2.4.3.2. Sections

This option would have separable sections that could be used to change the length of the wand. For instance, to reach a high spot, the user would add more sections, or take out sections to reach a low spot.

Pros of a sectional wand include:

- Adjustable reach
- Fairly simple design
- Fairly easy to integrate fluid/power paths
- Collapses for storage

Cons of a sectional wand include:

- Must stop to change reach
- Possibility of leakage at joints
- Multiple sections to carry, store, keep track of
- Difficult to manufacture

2.4.3.3. Telescoping

This wand would telescope to reach higher and lower sections of the sign, and would lock into place at certain intervals to prevent unwanted collapse.

Pros for a telescoping wand include:

- Reach is easily adjusted
- Collapses for storage

Cons for a telescoping wand include:

- Complex design
- Difficult to integrate power/fluid paths
- Difficult to manufacture

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2.4.4. Cleaning Fluid Delivery

This section outlines the possible methods of delivering cleaning fluid to the end effector. Three options are considered: a powered pump, a manual pump, and no pump at all. The last option has the chemical being applied at the point of use by a remote trigger.

2.4.4.1. Powered Pump

This option would use power from the tool's power plant to operate a motorized pump, most likely a 360° peristaltic pump, because this type of pump has a consistent output flow for a low power input.

Pros of using a powered pump include:

- Less effort for operator
- May use thicker liquid

Cons of using a powered pump include:

- Requires power, thus a larger capacity battery or engine
- Heavier
- More expensive

2.4.4.2. Manual Pump

This option would have the worker pump the cleaning fluid by hand.

Pros of using a manual pump include:

- Cheaper
- Lighter
- Does not require power from tool

Cons of using a manual pump include:

- More work for operator
- May not work with thick liquids

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- May not be able to pump to necessary height
- Risk of repetitive stress injury, such as carpal tunnel

2.4.4.3. Application at End Effector

This option does not use a pump at all, but instead alters the form of the end effector to allow integration of a container of cleaning fluid. This would most likely work only with products that come in pressurized containers, and would require some sort of remotely operated triggering mechanism.

Pros of applying the cleaner at the end effector include:

- No effort from operator
- Cheaper (no pump necessary)

Cons of applying the cleaner at the end effector include:

- Only works with certain cleaners
- Increases mass of end effector

2.4.5. Solvent Capture and Disposal

This section outlines the choices for the capture and disposal of the solvent that has been used to clean the sign. Two options are considered: a disposable absorbent pad, and a motorized vacuum sucking solvent into a tank.

2.4.5.1. Absorbent Pad

This option would use an absorbent pad, most likely attached to the end effector, which would be used to wipe the sign after cleaning, absorbing any excess cleaner. The operator would replace it when it became saturated with solvent.

Pros of using an absorbent pad include:

- Inexpensive

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- Light
- Requires no power

Cons of using an absorbent pad include:

- Increased waste, likely considered hazardous
- As it becomes saturated, it is more likely to drip solvent (which is to be avoided)
- As it becomes saturated, it would smear paint and solvent on the sign

2.4.5.2. Vacuum into Tank

This option would use a motorized vacuum to apply negative pressure to the sign, which would suck any excess solvent off of the sign and deposit it into a waste tank on the tool. In order to avoid overheating the motor, there must be air passages on the end effector to allow air to flow to the face.

Pros of using a vacuum include:

- Less waste
- Applies pressure to sign, which will help clean paint
- Prevents excess solvent from dripping

Cons of using a vacuum include:

- Requires power
- May require large flow rate
- Noisy
- Heavy
- Costly

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2.4.6. Form of End Effector

The methods that may be used to clean a sign are limited to chemicals and a cloth or something similar to scrub, and a laser. Since laser-based systems were developed in the early-to-mid 90s, and yet are not in use today, it is assumed that their cost and complexity is still prohibitive to their widespread adaptation. Therefore, the end effector shall consist of the former method for graffiti removal, in the form of brushes or pads scrubbing the sign.

This section examines two possible shapes for the face of the end effector: square and triangular.

2.4.6.1. Square

This option would have the face of the end effector be square. Most signs that would need cleaning are rectangular in shape

Pros of having a square end effector include:

- Fits most signs
- Larger area covered by end effector

Cons of having a square end effector include:

- May not fit irregularly shaped signs (e.g. CA state route)
- More cost
- More mass

2.4.6.2. Triangular

This option would have the face of the end effector be an equilateral triangle. This would allow it to fit more signs, though the cleaning area is reduced.

Pros of having a triangular end effector include:

- Fits irregularly shaped signs

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- Lower mass
- Lower cost

Cons of having a triangular end effector include:

- Less area covered by end effector

2.4.7. Method of Ensuring Sign is Not Damaged

This section examines possible methods for ensuring that the sign has not been damaged from the cleaning. There are essentially two ways to do this: check the sign with a retroreflectometer, or be reasonably assured from previous testing that the methods of cleaning do not damage the sign.

2.4.7.1. Retroreflectometer

This option would use a retroreflectometer to check the sign's reflectivity after cleaning. While this would give instant feedback, they tend to be quite expensive (~$5000-$12,000 off-the-shelf) and heavy (2-3kg). To include one in the end effector would immediately make it more expensive, heavier and more delicate.

Pros of using a retroreflectometer include:

- Instant feedback on sign's state
- May be used solely to check a sign's reflectivity

Cons of using a retroreflectometer include:

- Very costly
- Heavy
- Delicate

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2.4.7.2. Assurance from Testing

This method would use information about the signs' susceptibility to damage, gathered from the manufacturer or other knowledgeable entity. However, no one currently knows how much scrubbing or pressure a sign can take before it is damaged [21]. Therefore, this method would require tests to be run on signs using the end effector in order to assure a design that does not damage the sign. Since testing would have to be done anyway in the course of tool development, this method is likely a better choice.

Pros of using testing include:

- Less expensive
- Lighter
- More robust design
- Needs to be done anyway, to some degree

Cons of using testing include:

- More time needed to develop design
- May not accurately represent actual situations (sign conditions, user behavior, etc)

2.5. Final Design Proposal

The proposed final design is to have a backpack mounted, battery powered tool, because this allows the most freedom in terms of worker travel and choice of vehicle. The end effector would be triangular in shape because this allows irregularly shaped signs to be cleaned. It would be on the end of a telescoping wand because this gives the greatest height range while maintaining a compact form, and it would not have a retroreflectometer integrated into it due to cost and robustness considerations. The

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solvent would be applied by a powered pump and recovered into a tank by a vacuum. A conceptual sketch is shown in Figure 2-2.

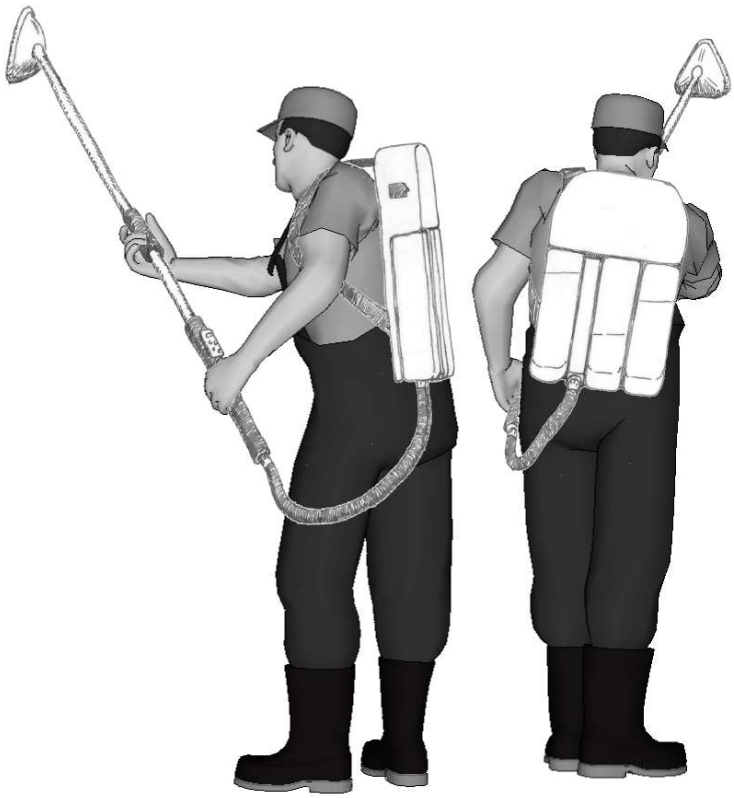

Figure 2-2: Conceptual sketch of sign cleaning tool

It should be noted that this is only an initial design proposal and will need to be developed further. For instance, the power requirements for extended operation of the vacuum system may be larger than can be feasibly supplied by battery, or the telescoping wand may increase the cost and complexity of the tool such that a static wand is a better choice. In any case, these concepts (and possibly others) should be further investigated, screened, scored and ranked, and the best one chosen.

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2.6. Conclusion

This chapter began by translating customer statements about the current graffiti removal process for signs into needs for a sign cleaning tool. These needs were assigned metrics whose values would determine whether or not the need was met by the proposed design. Then, several possible aspects of the design were examined and weighed, and a final design was proposed.

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Chapter 3. Development of the End Effector

3.1. Introduction

At this point in the report, the focus on development of the sign cleaning tool shifts from the overall tool to only the end effector. A critical issue revolves around the nature of the end-effector and its interaction with, and effects on, the signs. Since it is imperative that the tool not damage the sign significantly, key characteristics of the end effector must be well-developed and well-tested before the overall design of the tool continues. Accordingly, this report has been directed towards developing an understanding of this complex interaction and to delay a final concept and detailed design for a later time when the experimental results of the later chapters can be reflected in the design.

This chapter begins by presenting a basic concept of the end effector. Next, it will cover the development and execution of a 2^4 factorial experiment aimed at determining the levels of damage the sign may incur from cleaning, as well as the necessary size of the motor in the end effector. Finally, it will cover the execution of further testing aimed at gaining other information about the performance of the end effector.

3.2. Basic Concept of the End Effector

Figure 3-1 shows a rough sketch of the proposed design of the end effector. As stated previously the end effector will apply the cleaning fluid, scrub the graffiti, and remove the cleaning fluid and dissolved paint. Of these three actions, the scrubbing is most likely to damage the sign. Additionally, as stated in Section 2.4.7, it is generally unknown what levels of pressure or types of brush material will damage the sign. Finally, because it is not known what levels of friction will occur during cleaning, it is not accurately known how much torque is needed in order to accomplish the scrubbing motion. This is

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important because it determines the size of the motor that will be used on the end effector, which in turn determines its mass and dimensions. Thus, before other development can continue, it is first necessary to determine these characteristics of the end-effector.

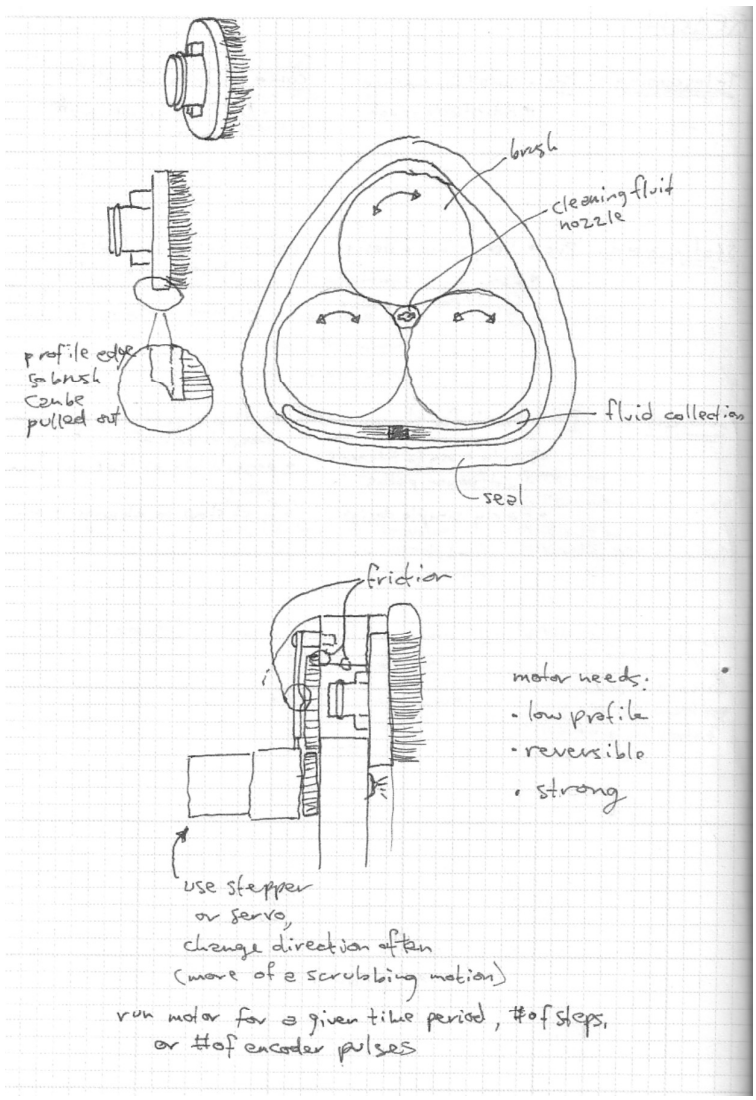

Figure 3-1: Conceptual sketch of end effector

3.3. Development and Execution of the 2^4 Factorial Experiment

In order to determine the size and speed of the motor used in the head, the amount of pressure that could be applied to the surface of the sign, and the types of brush used by

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the end effector, it was necessary to run tests on sign samples to determine what levels of these values, if any, caused damage to the sign and therefore should not be used. Damage to the sign is measured as a significant reduction in the coefficient of retroreflectivity, caused either by damage to the retroreflective layer or by damage to any superior layer (e.g. clouding or scratching the anti-graffiti coating). A reduction in R_A is considered significant if five "cleanings" would reduce R_A by greater than 70 per cleaning, on average.

To determine the reduction in R_A from the sign cleaner, a statistical approach was used in the form of a 2^4 factorial experiment, where each possible combination of four factors would be tested. The purpose of the test was to determine which combinations of pressure, speed, brush type and sign coating were the most likely to result in a damaged sign, as well as to develop a regression model capable of predicting the amount of damage to a sign when a given combination of these factors was used. The four factors and their levels are shown in Table 3-1.

Factor	Low level (-)	High level (+)
Axial load	7.78 N (1.75 lbf)	37.81 N (8.48 lbf)
Speed	28.5 rpm	65 rpm
Brush type	Polypropylene bristle	Scouring pad
3M 1160 film present	No	Yes

Table 3-1: Levels of factors in experiment

There are a total of 16 possible combinations of the factors, and in order to ensure statistically significant results, three replications of the test were taken, for a total of 48 data points. The run order of each replicate was randomized in order to eliminate any unaccounted-for variables (e.g. brush wear, etc.).

A secondary purpose of running the test was to measure the amount of torque generated during the tests, which would be used to determine the necessary motor size.

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Because the motor driving the brushes in the final design is contained within a head mounted at the end of a long pole, it is important that the motor be strong enough to clean the sign, yet light enough to allow it to be held by the operator for the length of time necessary to clean the graffiti.

After the first group of tests was run, a second group was run, examining the effects of a polystyrene brush on the sign; then a third group examining the effects of cleaning a painted sign; then a fourth group examining the effects of multiple cleanings on both painted and unpainted signs..

3.3.1. Setup

3.3.1.1. Sample Signs

The samples under test were 15.24 cm (6 in) square panels of 6061-T6 aluminum coated with plain white 3M Series 3930 High Intensity Prismatic retroreflective sheeting (Figure 3-2). Half of the sign samples also had an additional coating of 3M 1160 Premium Protective Overlay Film (anti-graffiti coating). These materials were chosen because they are the most commonly used by Caltrans in road signage, and also because the prismatic film is the most susceptible to pressure damage from improper cleaning. White signs, as opposed to another color, were chosen due to price considerations and the fact that only reductions in R_A relative to a new sign are being measured.

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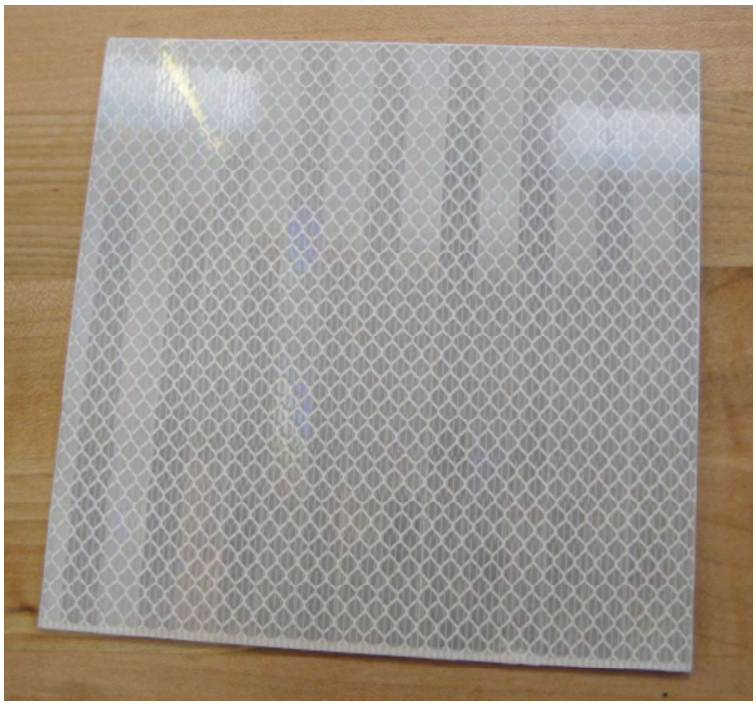

Figure 3-2: Typical sign sample used in test

3.3.1.1.1. Control Sample

In order to compare the degradation of the sign, a set of new, untouched sign samples were used as a control. Five samples of each type of sign were taken randomly from the batch of signs used in the tests. Their R_A was taken in three spots on each one, for a total of six measurements per sign: one in the center of the sign, one at the center of the top edge, and one at the center of the right-hand edge (Figure 3-3). These readings were averaged together for each sign, and then the five values for each sign were averaged together to provide one control R_A value for each type of sign (with 1160, and without 1160). The results can be seen in Table 3-2. The control values were taken only once.

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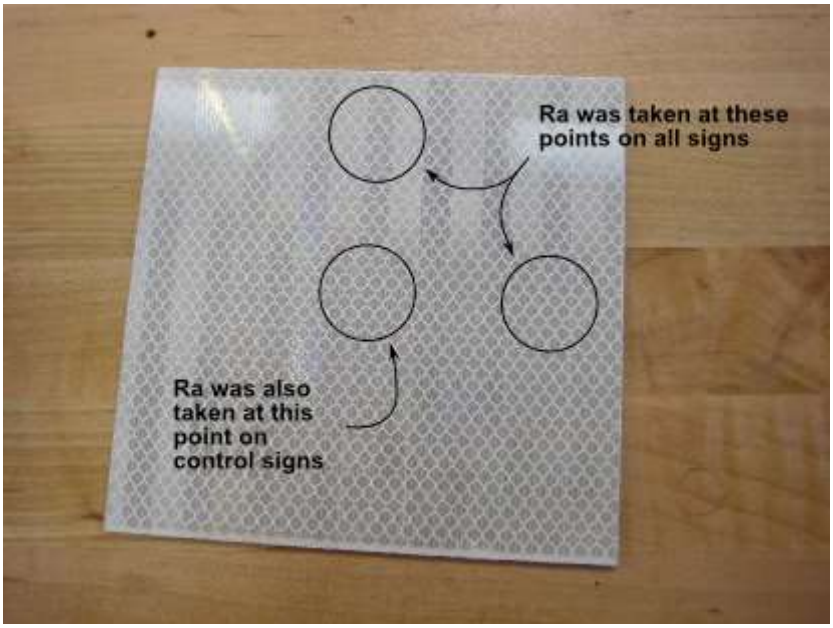

Figure 3-3: Location of test areas on sign samples

3.3.1.2. Test Fixture

The main structure for the test fixture was a Makita drill press stand, the normal function of which is to allow one to use a normal hand drill as a drill press; however, its purpose for this test was to allow different pressures to be applied to the sign surface. It had a carriage that was moved vertically by lowering and raising a handle, and masses were hung off of the handle to allow the different pressures to be applied to the sign. Figure 3-4 shows the test fixture in use.

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Figure 3-4: Test fixture in use

The motor used in the test fixture was a reversible 12 VDC 100 rpm 24.9 W (1/30 hp) gearmotor, which could generate 2.26 N-m (20 in-lbs) of torque and pull 6 amps continuously at no-load conditions. This motor was chosen based on basic calculations of the interface between the brush and sign. The coefficient of friction (COF) data that most closely represented the brush-sign interface was that for polystyrene sliding on polystyrene, for which the static COF is 0.5 (kinetic unavailable) [30]. Since the static COF is generally higher than the kinetic COF and since the sign surface was to have cleaner applied to it which would act as a lubricant, this value was taken as the worst-case scenario and used in the motor-size calculations for the test stand. Because the test fixture uses flexible bristle brushes, it was assumed that axial loads would result in

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uniform pressure over the surface of the brush during testing. From the uniform pressure model for frictional-contact axial clutches [31], the torque resulting from a given axial force can be calculated by

$$T = \frac{Ff}{3}\frac{D^3 - d^3}{D^2 - d^2} \tag{3.1}$$

where F is the axial force, f is the COF, D is the outer diameter of the clutch, and d is the inner diameter. The brushes to be used were 12.7 cm (5 in) in diameter and covered the entire surface (d=0), and the axial load was to be no more than 9.1 kg (20 lbs) (and ended up being much less). This resulted in a maximum predicted torque of 1.89 N-m (16.7 in-lb). The motor chosen exceeded this value slightly to avoid its being anywhere near stall condition during the test.

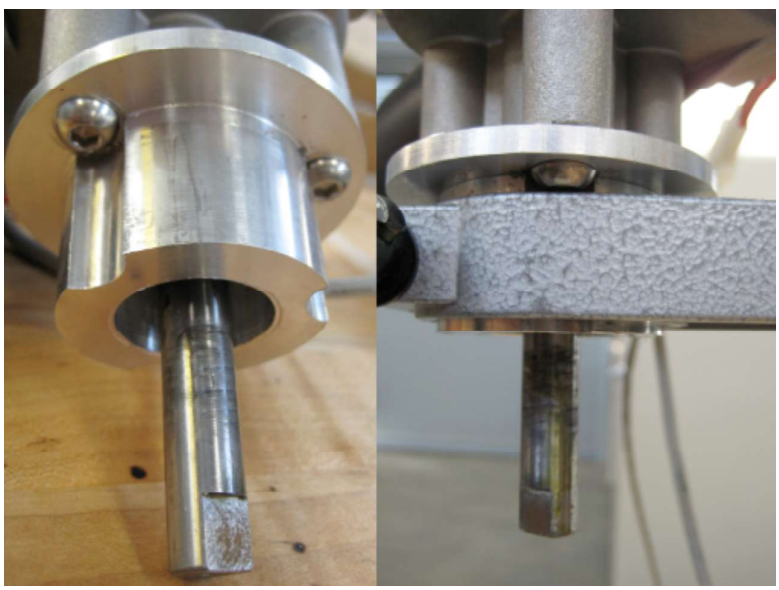

Figure 3-5: Flange motor mount. Left: bolted to motor. Right: clamped in stand.

In order to fit the motor into the carriage of the test stand, a flange mount was machined from aluminum (Figure 3-5). This flange attached to the motor mounting holes on the motor and clamped into the collar of the carriage. It also had a hole bored

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lengthwise through its center which allowed passage of the motor shaft. The shaft was in turn coupled to the brush by a rigid aluminum two-piece clamp-on shaft coupling, which was turned down a bit on a lathe in order to reduce the inertial load it presented to the motor (Figure 3-6).

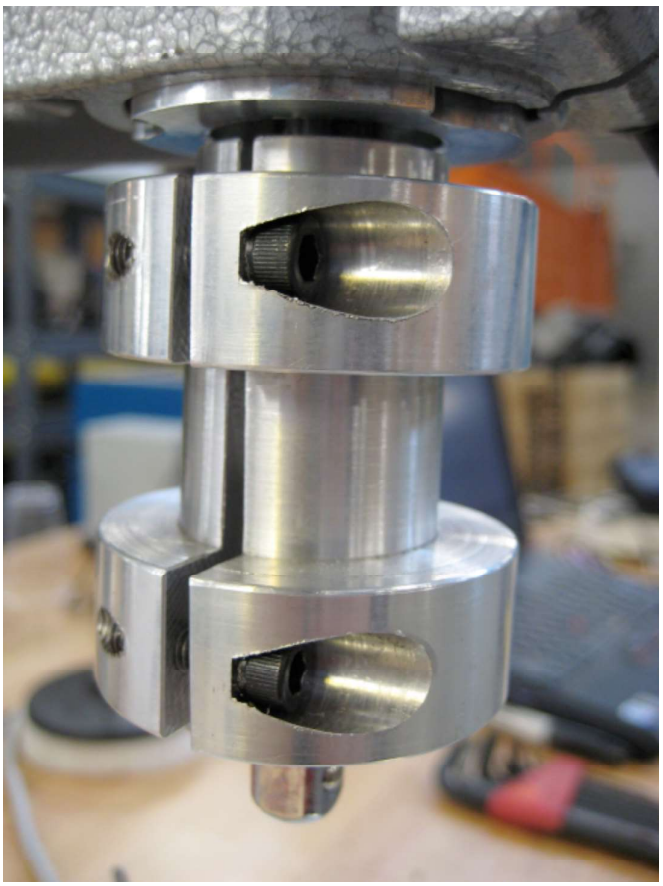

Figure 3-6: Coupling from shaft to brush

Because a few different types of brushes would be tested, it was advantageous to be able to rapidly change the brushes, as well as move them out of the way so that sign samples could be loaded and unloaded from the test bed. This was achieved by inserting a 1/4" to 3/8" socket driver adapter into the coupling, such that the 3/8" side stuck out of the bottom. Then, a 3/8" drive 5/16" hex bit socket, with the bit removed and the brush's

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drive shaft in its place, was attached to that, such that the brush could be rapidly moved or changed (Figure 3-7).

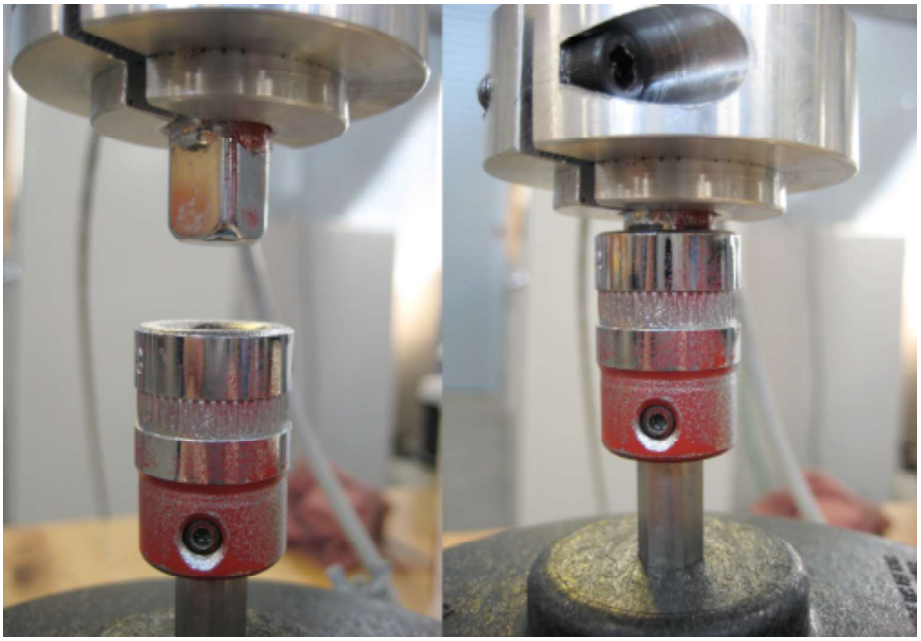

Figure 3-7: Brush connection to clamp-on coupler

The bed on which the sign samples were tested was comprised of a flat plate on which the samples were placed, and a frame that covered the sign along its edges and held it immobile for the test. This frame was attached to the plate by four dowel pins (which prevented rotational motion and allowed quick registration of the frame to the plate) and four wingnut and machine screw combinations (which provided clamping force on the sign) in slots along the upper and lower edges of the frame and plate. Slots were used rather than holes so that the signs could be quickly and easily changed; the wingnut and machine screw combinations needed only to be loosened slightly in order to be removed and the sign sample changed, rather than having to completely disassemble any hardware (Figure 3-8). The flat plate was rigidly attached to a flange-to-flange mount torque sensor, which in turn was rigidly attached to a load sensor, which in turn was rigidly

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attached to the bed of the Makita fixture (Figure 3-9), and the entire test stand was rigidly clamped to a table.

Figure 3-8: Detail of test bed showing frame attachment method

Figure 3-9: Torque cell and load cell affixed between test bed and stand

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3.3.1.3. Brushes

Two different types of brushes were used for the first test, both manufactured by the same company (Tucel Industries, Inc.) and attached to the test fixture the same way. One was a polypropylene bristle brush (Figure 3-10, left), with bristles about 2.54 cm (1 in) in length, an inner diameter of about 6.35-7.62 cm (2.5-3 in), and an outer diameter of 12.7-13.3 cm (5-5.25 in), depending on the amount that the bristles spread out due to the load. The other was a scouring pad (Figure 3-10, right) made of an unknown material with a diameter of 12.7 cm (5 in). The pad itself was replaceable, and attached to the base by small hooks, much like hook-and-loop fasteners (Figure 3-11). These materials were chosen because of the contrast in the way each behaved when moving across the sign. When the brushes changed direction, the bristles underwent a large amount of bending while their tips remained stationary. This caused a spike in the force being applied to the sign by the brush, which subsided once the bristles began their sliding motion in the opposite direction. If a sign were to be subject to pressure damage, it is possible that a significant amount would happen at that point.

Figure 3-10: Brushes used in tests. Left: Polypropylene; Right: Scouring Pad

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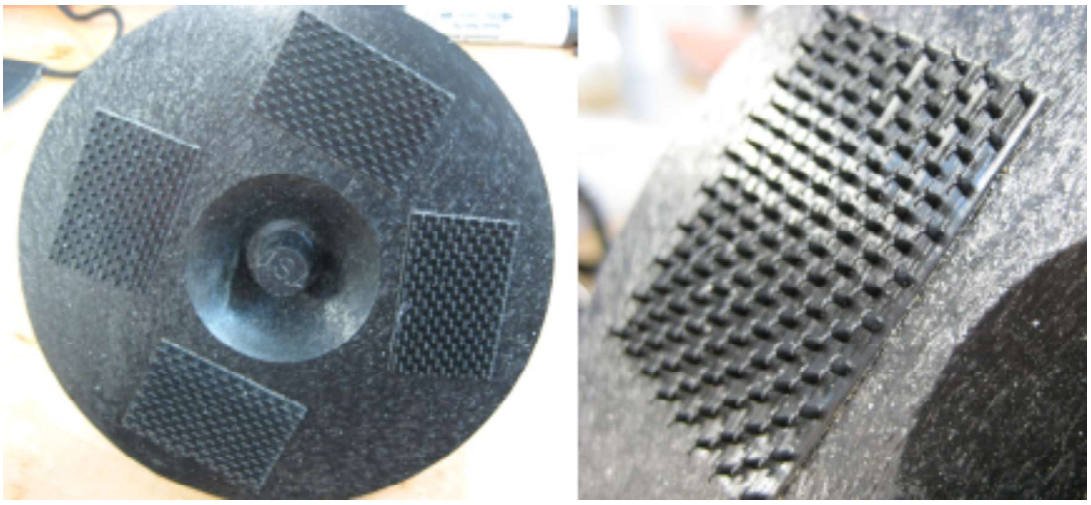

Figure 3-11: Hook-and-loop attachment for scouring pad

For the second and third tests, a polystyrene brush manufactured by Grainger, Inc. was used (Figure 3-12). This brush had an outer diameter of 13.3 cm (5.25 in) and an inner diameter of 3.81 cm (1.5 in) with 2.54 cm (1 in) bristles, and had a 0.95 cm (3/8 in) shaft that fit into the shaft coupling. This brush's bristles were softer than those of the polypropylene brush, but were still resistant to chemical damage.

Figure 3-12: Polystyrene brush

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3.3.1.4. Loads Applied to Sign

In order to vary the load applied to the sign during the test, two different amounts of mass were hung statically on the handle of the test fixture for the duration of each run. These masses were 1.08 kg (2.38 lbm) for the low level, and 1.96 kg (4.32 lbm) for the high level, which resulted in axial loads at the sign surface of 7.78 N (1.75 lbf) and 37.81 N (8.5 lbf) due to the fact that the handle was a second-class lever. It should be noted that, because the brushes used covered different areas, the pressure applied to the sign varied depending on the brush being used. For the bristle brush, which had an area of 81.1 cm^2 (12.6 in^2) for the low load and 107.3 cm^2 (16.6 in^2) for the high load, the pressure was 0.96 kPa (0.14 psi) for the low level and 3.52 kPa (0.51 psi) for the high level. For the scouring pad, which had an area of 126.7 cm^2 (19.6 in^2), the pressure was 0.61 kPa (0.09 psi) for the low level and 2.98 kPa (0.43 psi) for the high level. For the polystyrene brush, which had an area of 127.5 cm^2 (19.7 in^2), the pressure was 0.61 kPa (0.09 psi) for the low level and 2.97 kPa (0.43 psi) for the high level. All of these pressures are close enough to each other that no attempt was made to correct for their differences by changing the amount of mass on the handle.

3.3.1.5. Chemicals

The chemical used for the experiment was SEI Graffiti Remover, which is on Caltrans' most recent Qualified Products List for graffiti removers [32].

3.3.1.6. Motor Control

The motion of the motor for the tests was chosen to be sinusoidally oscillatory, rather than unidirectional, for two reasons. First, oscillatory motion was chosen as a design feature because it most closely imitates the motion that a worker would use to clean a sign, which is back-and-forth scrubbing. This motion is believed to be more effective

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than unidirectional scrubbing because it subjects the paint film to oscillating shear forces and is thus more likely to remove the paint. Second, the reversal of the bristle brush may cause damage, which is worth investigating.

To obtain the motion, a variable frequency and amplitude signal was generated by the LabVIEW VI and sent through the digital acquisition card (DAQ) to a class D amplifier (schematic shown in Figure 3-13), which generated an amplified pulse-width modulated (PWM) signal, which was then sent to the motor. Two speeds were used for the test: ~30 rpm, and ~65 rpm, on average, for the low and high values. Neither of these was completely exact due to the changing loads that were presented to the motor from the brush type and the axial force.

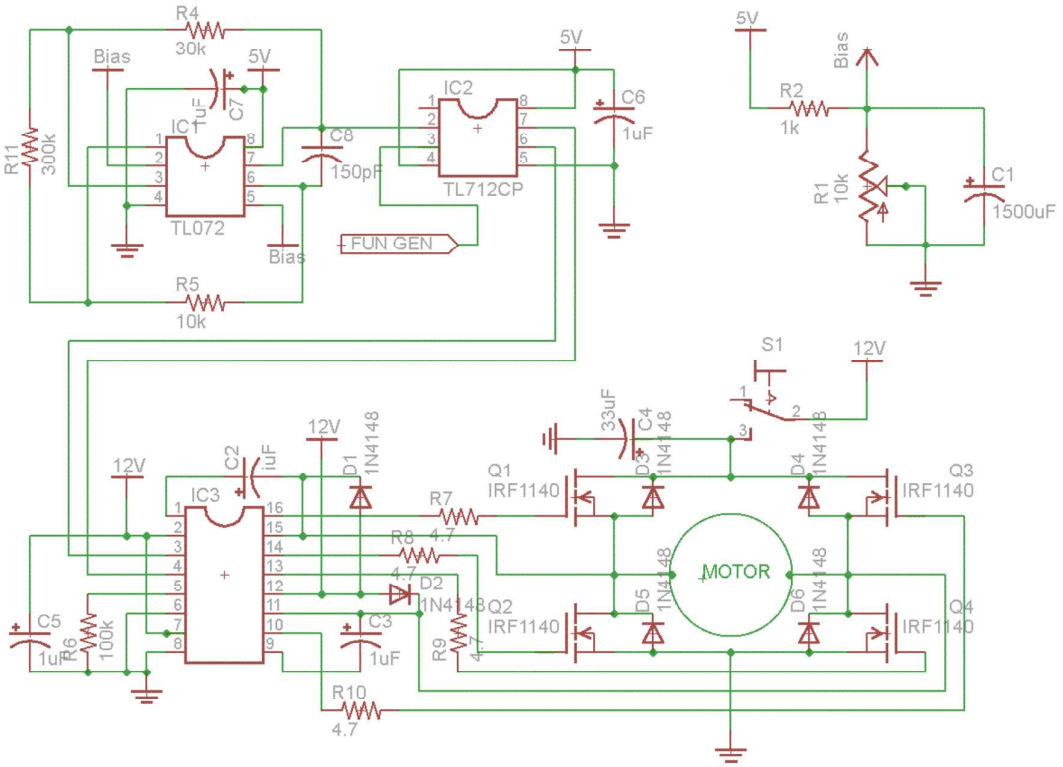

Figure 3-13: Class D PWM driver schematic

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3.3.1.7. Instrumentation

Three characteristics of each test were measured: the rotational rate at which the brush moved, the amount of torque the brush exerted on the sign, and the amount of force the brush exerted on the sign. Each of these values was input to a LabVIEW virtual instrument (VI) which recorded and took long-term average values (over 40 cycles) of their characteristics.

The rotational rate was measured by a Accu-coder 755A incremental rotary encoder with an output of 2500 pulses per revolution (Figure 3-14). This encoder was attached to the output shaft of the motor by physically altering the motor's stock construction. This involved cutting a hole in the backplate of the worm gear box and adding a shaft extension that stuck out of the hole. The encoder was then attached to this shaft extension, and the body of the encoder was rigidly attached to the backplate of the worm gear box. The output of the encoder was routed to a National Instruments USB-6229 16-bit DAQ card for input to the VI.

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Figure 3-14: Encoder attached to back of motor

The torque exerted on the sign was measured by a TQ-301 flange-to-flange mount torque sensor from Omega Engineering, Inc., which was comprised of a full Wheatstone bridge strain gauge circuit capable of measuring from 0 to 45 N-m (0-400 in-lb) of torque. The output of the torque sensor was 2 mV/V, and with a 10 VDC excitation, the expected full-scale output of the sensor would be 18 mV at 45 N-m of torque. This means that for this particular application, with a maximum applied torque of around 1.89 N-m (16.7 in-lb), the maximum output was roughly 0.76 mV, which was then filtered and amplified (discussed later).

The load exerted on the sign was measured by an SSM-50 surface stud-mount load cell from Transducer Techniques, which was comprised of a full Wheatstone bridge strain gauge circuit capable of measuring from 0 to 222 N (0-50 lbf). The output of the load cell was 2 mV/V, and with a 10 VDC excitation, the expected full-scale output of

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the sensor would be 1.76 mV at 222 N. This means that for this particular application, with a maximum applied load of around 38 N (8.5 lb), the maximum output was roughly 0.30 mV, which was then filtered and amplified.

Both the torque and load sensor outputs required filtration and amplification before being digitized by the DAQ card. Filtration was accomplished using a Sallen-Key topology, which creates an active 2nd order low-pass Butterworth filter, with the cut-off frequency set at 50 Hz in order to filter out any high-frequency noise. Due to having such a low-level output, the filter for the load cell also incorporated a gain stage of 2. The filtered signals were then sent to an instrumentation amplifier, where they were boosted by a gain of 800 (Figure 3-15). Finally, these signals were routed to the DAQ card.

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