Automotive Spray Paint Simulation

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Abstract. A system is introduced for the simulation of spray painting. Head mounted display goggles are combined with a tracking system to allow users to paint a virtual surface with a spray gun. Ray tracing is used to simulate droplets landing on the surface of the object, allowing arbitrary shapes and spray gun patterns to be used. This system is combined with previous research on spray gun characteristics to provide a realistic simulation of the spray paint including the effects of viscosity, air pressure, and paint pressure. The simulation provides two different output modes: a non-photorealistic display that gives a visual representation of how much paint has landed on the surface, and a photorealistic simulation of how the paint would actually look on the object once it has dried. Useful feedback values such as overspray are given. Experiments were performed to validate the system.

1 Introduction

Training spray painters to apply modern paints can be an expensive process. Paints can vary significantly in how they must be applied to a surface, forcing painters to vary spray gun settings, speed of spray gun movement, and distance of the gun from the surface of the object. Therefore, training new painters can be costly in both time spent training the painter and in amount of paint used. Even experienced painters may need to re-train for newly formulated paints that require careful application techniques to achieve proper results. When working with real paints, this training must be performed in an expensive spray booth with both the instructor and the pupil wearing protective clothing and bulky respirator masks.

The goal of the virtual reality system described in this paper is to aid in training painters to use spray paints thereby reducing the amount of paint and time wasted in training. In addition, this system can be used by paint designers to determine how difficult a new paint would be to spray, without having to actually manufacture and test the paint. The system provides users with many useful features, including: photorealistic and non-photorealistic visualization of paint thickness, numeric feedback on overspray and other relevant variables, customization of spray gun settings, and a realistic spray painting environment. In addition, the system has been validated with user testing on real spray painters.

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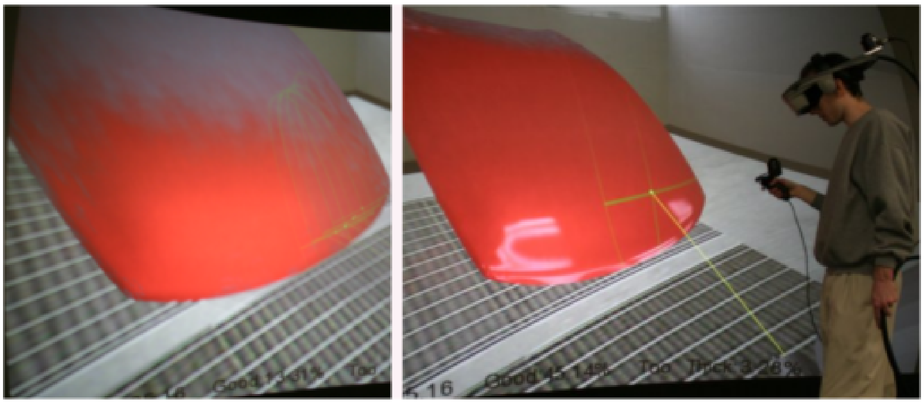

Fig. 1. Left: Photorealistic rendering (as seen in headset) of directionally diffuse paint on a car hood. Note that some minor artifacts can be seen from too few rays being used to simulate the gun. Right: The final result of the painted car hood after a gloss coat has been applied.

2 Relevant Work

The two most relevant pieces of research describe basic spray paint simulation for the ship building industry [Yang et al. 2007] [Kim et al. 2007]. Yang et al. employs a tracked spray gun and head tracker to place the user in a virtual environment. The user then sprays the virtual object with the spray gun, and gets feedback on the resulting paint thickness. Kim et al. uses a spray paint simulation that employs ray casting and a flood fill algorithm to fill the nearby texture pixels next to the striking coordinate spot. Our algorithm makes use of pre-computation of texture density to perform "splatting" in constant time (see Section 3.1). The approach described in this paper supports arbitrary object shapes.

The research and resulting system described in this paper goes beyond the above systems in several ways. First, a realistic paint color model was added, allowing users to view a photorealistic simulation of the resulting paint job rather than just a paint density texture map, including a realistic lighting environment. Second, parameters that can change how paint must be applied such as air/paint ratio and paint viscosity are modeled in the simulation. Finally, user testing with the system was performed to both improve it and validate it as a training tool.

The photorealistic paint simulation used in the system was originally developed by Shimizu et al. [1]. The technique for paint simulation given in that research was altered to work with the other portions of the spray painting simulation (see Section 3.3). The method for capturing environment map lighting was first created by Debevec et al. [2] in which multiple pictures are taken at varying exposures to capture a high dynamic range photograph of the surrounding environment.

3 Setup and Spray Paint Simulation

Figure 1 shows the critical components of the virtual spray paint system. A tracked head mounted display allows the user to navigate around a virtual environment. The user holds a tracked "spray gun" that is used to spray paint objects placed in the environment. The system currently works with any head mounted display and either a magnetic or optical tracking device. An nVis 1280x1024 resolution head visor along with a HiBall optical tracker was used for testing the system.

3.1 Simulation of Paint Particles

A natural method to simulate spray painting is ray casting, because casting a ray toward a virtual surface is very similar to a paint particle striking a real surface. However, since any drop below a real time frame rate could result in improper training, calculating a ray cast for every paint particle is computationally infeasible.

Fortunately, a good compromise between realism and rendering speed can be accomplished by firing fewer rays, and having each ray that strikes the surface spread paint over a reasonable area. Thus, each particle fired from the spray gun is intersected with the virtual object using a ray cast calculation, and "splats" onto the surface, much as a real particle of paint would do. Varying the size of the splat allows more or fewer rays to be used, allowing a balance between realism and rendering speed.

The first step in the spray simulation is to sample the mesh at load time to determine *uv* density: the area of the *uv* triangle (determined by the texture coordinates and texture size) divided by the area of the 3D triangle (determined by the 3D position coordinates). The *uv* density of each triangle is then stored for later use in paint "splatting."

When the spray gun's trigger is pressed, a number of rays are generated, each with an origin of the spray gun's nozzle tip, and a direction chosen within the shape of the spray cone. Each ray is tested with the virtual object to determine the intersection location, both in 3D space as well as *uv* texture space using barycentric coordinates [3].

After the precise intersection point has been determined, the paint density on the affected portions of the object must be updated. The paint density is stored as a texture map across the surface of the object. In addition to the precise texture coordinate that each ray hits, a "splat" is performed to affect nearby texels as well, based on the pre-computed texture density performed above. Splat size is based on a world coordinate area, then translated to a size in texels based on the pre-computed *uv* density (rounded to the nearest texel).

Once it has been determined which texels in the density map should be updated, the precise amount to increase the value of each texel must be calculated. This quantity is the amount of paint represented by the ray multiplied by the percentage of the total splat area that the texel represents. The amount of paint each ray represents is based on many factors, including the total rays being cast, the characteristics of the gun being used, and the distance from the gun to the object (paint is lost as particles travel from the gun to the object). See Section 4 for details on the effects of distance and gun settings on the amount of paint that reaches the object surface.

In the current system, rays are cast 30 times/second and both splat size and the number of rays to be cast are user set parameters. If too few rays are cast and/or the splat size is too small, the visual effect of the spray going onto the surface of the object can become "splotchy." This can be seen in Figure 1. The exact number of rays and splat sizes required to prevent this appearance varies with the size of the area the gun is spraying at any given moment, which is a function of the spray gun settings and the distance of the gun from the surface.

The number of rays that can be cast per frame while maintaining 30 frames per second varies with the number of polygons in the paintable object. In practice, an object with 10,000 polygons can be run at about 500 rays per frame on a Pentium 4 2.8 ghz single core processor, while a 10 polygon flat panel model will run at about 2000 rays per frame. The splat size is then scaled appropriately to generate an even appearance on the surface. Generally, the splat size can be kept to just one neighboring texel with acceptable visual results. However, larger splats may be necessary for high polygon count models (high cost ray casting) or large textures (high uv density).

Using the above approach, a density map is built up on the virtual object representing the thickness of the paint at each point on that object. This can then be used to give output back to the user on how well the painting has been performed.

3.2 Non-Photorealistic Display Algorithm

The first method of user feedback is a non-photorealistic (NPR) display. This method takes the thickness data from the texture map and attempts to visualize it in a manner that allows the user to immediately judge exactly how thick and uniformly the paint has been applied. This is an excellent way to provide training information to new painters, or discover defects in an existing paint procedure.

The algorithm for performing this is relatively simple. A 1D texture of colors is created and passed into the shader. The thickness data that is stored from the paint particle simulator described in Section 3.1 is used to index into the 1D texture and retrieve the proper color for that texture pixel. The 1D texture that is currently used in the system is a common cold-hot color scale, ranging from blue to yellow to red as the paint becomes thicker. Areas that are light blue have too little paint, deep blue the correct amount, yellow warns that the paint is about to become too thick, and finally red indicates that too much paint has been applied. The rate as which the thickness moves through these colors can be controlled by a script, allowing users to easily set the proper paint thickness for a particular paint being simulated. See Figure 2 for an example of the NPR display algorithm at work.

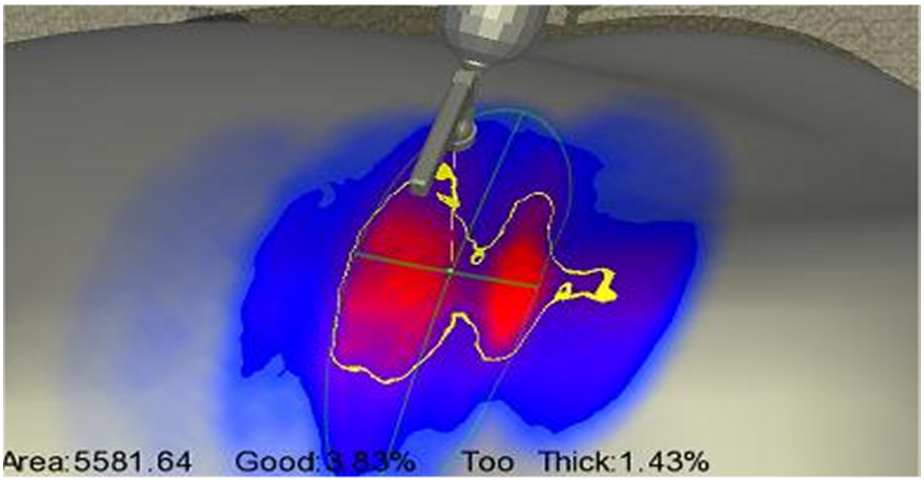

Fig. 2. An NPR rendering with a shape that has been painted using a range of thicknesses. A cold-hot color visualization scheme has been used to show the user the thickness of the paint. Here, the white region (normally yellow) separates the region of too thick (light, normally red) from properly painted (dark, normally blue).

3.3 Photorealistic Display Algorithm

In addition to an NPR algorithm, a photorealistic rendering algorithm was implemented. This algorithm is a modification of a metallic car paint simulator described in [1]. The metallic paint simulator allows a user to design a paint color, and then displays it on a model using environment map based lighting.

For the spray painting simulation, a couple modifications were made: first, the gloss portion of the simulation is separated from the directionally diffuse color. This allows a user of the virtual system to realistically spray the diffuse color of the metallic paint before applying the final gloss coat, just as a real spray painter does. Second, the simulation was modified to permit the paint to become “lighter” or “darker” based on the thickness of the paint (Beer’s law). This allows the paint to appear more realistic as it being applied in real time. A similar effect can be done with the gloss, allowing the surface to appear more or less glossy based on how much gloss has been applied. Figure 1 shows this rendering with both a partially complete diffuse coating as well as a fully painted object.

Another important aspect of displaying a realistic simulation to a painter is to place them in a familiar environment. Modern paint shops have paint booths designed to give the painter a lighting setup best suited to showing any defects in the paint job. Therefore, we have taken care to capture a real paint booth environment using high dynamic range photographs, which is used as the environment in which to paint (see Figure 3). The painted object is also properly lit using this environment [2]. The system also allows users to input their own lighting environments to use if they wish.

4 Spray Paint Parameters

Simply allowing a user to spray a surface with a virtual spray gun and observe the resulting paint thickness leaves out a critical fact: not all paints spray onto a surface in the same way. Changing the spray gun can also have a dramatic effect on the application of the paint. Factors such as air pressure, paint pressure, and viscosity of the paint must be taken into account when determining the final appearance of the painted object. For instance, paints with more solid particles (higher viscosity) tend to travel further, resulting in more paint landing on the target compared to a paint with lower viscosity. However, a much higher paint pressure must be applied to achieve the same flow rate with the higher viscosity paint.

The simulation presented in this paper makes use of research performed by [4]. Kwok did trials of spray painting using differing paint spray gun characteristics. The resulting distribution of paint on a target surface was carefully measured for a variety of variables. By using the results of this study, variables have been added to the simulation: viscosity, A/P ratio (the ratio of air pressure to paint pressure), target distance, paint flow rate, and spray gun cone size can all be controlled by the user with realistic results. For instance, the amount of overspray (paint that misses the target, either due to hitting something else or to evaporation) varies approximately linearly based on the distance of the gun to the target. Table 1 shows the effects of a few of the more important variables that are used in the simulation. Figure 4 shows how varying the parameters of the spray paint can affect the final visual appearance of the painted object.

The use of these variables allows the simulation to be tailored to a particular paint with little effort. A new paint's characteristics can simply be input to the simulation, and painters can practice painting without wasting large quantities of potentially expensive paint.

One extremely important aspect of spray painting that these variables affect is overspray. Overspray is undesirable for a number of reasons. First, it is a waste of paint, costing the paint company money in materials. Second, stray paint particles can potentially fall on portions of the object or work area that will have to be cleaned later. Finally, overspray lost into the air can become a health and environmental risk.

Variable	Value	Paint Deposition (gm)	Overspray (%)
A/P Ratio	0.92	4.14	22.32
A/P Ratio	1.49	3.54	31.69
A/P Ratio	2.18	3.19	39.69
Viscosity(cstk)	57	3.54	31.69
Viscosity(cstk)	106	4.32	25.44
Distance(inches)	7.00	4.59	21.93
Distance(inches)	10.00	3.54	31.69
Distance(inches)	14.00	2.75	45.99

Table 1. An excerpt from [Kwok 1991] showing some of the variables that alter the amount of spray deposition that lands on the target. In all cases, the paint flow rate was kept constant at approximately 275cc/min.

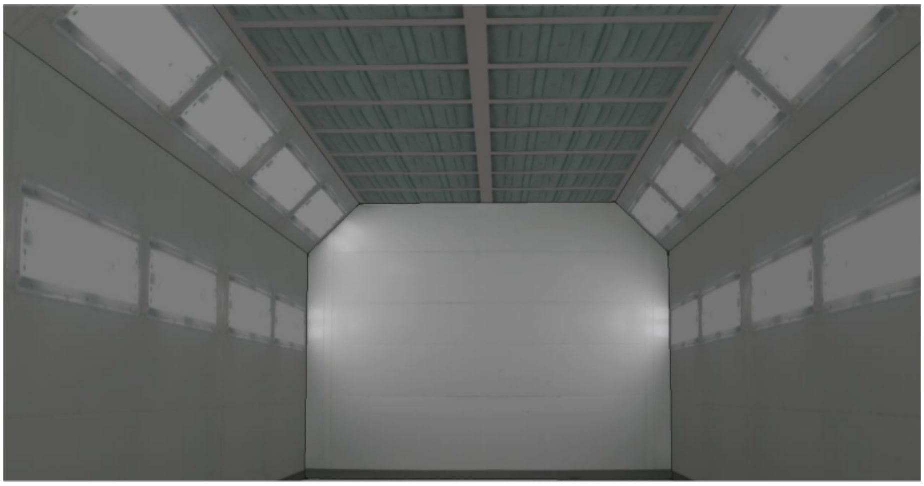

Fig. 3. The model of the spray booth. Both a model and environment map have been constructed. This allows a painter to use the virtual system in an environment that is familiar to him/her.

However, many of the parameters that reduce overspray may also make a paint more difficult to spray. During user testing, when spray painters were asked to make adjustments to the spray gun until it sprayed correctly, they tended to adjust the settings in directions that caused greater overspray. A strong advantage to using the virtual training system is that overspray is accurately calculated (utilizing the research performed by Kwok) and displayed back to the user at all times. Therefore, this system provides an effective method for evaluating new spray paints and for reaching a good compromise between ease of use and overspray.

5 User Studies

The system has been tested with both controlled experimentation as well as field testing in actual spray paint companies. The controlled experiments consisted

Variable	Expert1 (Real Paint)	Expert2 (Virtual Paint)	Novice (Virtual Paint)
Gun Dist (1st Coat)	5in.	6in.	6-10in.
Gun Dist (2nd Coat)	6in.	7in.	N/A
# Passes (1st Coat)	11	10	5
# Passes (2nd Coat)	8	6	0
Time (1st Coat)	33secs	38secs	50secs
Time (2nd Coat)	16secs	13secs	N/A
Correct Coverage (%)	100.0%	97.4%	79.9%

Table 2. The first experiment: An expert was tracked spray painting a panel. Then, the same setup was recreated virtually and painted by another (different) expert as well as a novice using the system.

Starting Settings	Painter1 Adjustments	Painter2 Adjustments
60.0% A/P 90.0% Flow Rate	Flow→130.0%	A/P→100% Flow→100%
120.0% A/P 140.0% Flow Rate	A/P→105% Flow→110%	Flow→90.0%
70.0% A/P 110.0% Flow Rate	Flow→125.0% A/P→100.0% Flow→105.0%	Flow→95.0% A/P→100.0%

Table 3. The second experiment. Two painters were asked to adjust the settings of the virtual spray gun back to their nominal settings (%100) after they had been altered. The painter adjustments are shown in the order in which the painters made them. Painters generally made adjustments in 10-15% intervals, so any adjustment that ended 85% to 115% was considered to be "close enough" to the original setting. This means all but one of the experiments ended with the painter properly adjusting the gun.

Variable	Expert	Novice
Car Hood % Correct	99.75%	60.0%
Car Hood Time	1min21secs	1min21secs
Car Hood Overspray	52%	40%
Car Hood Gun Dist.	10-11 inches	6-10 inches
Motorcycle % Correct	98.0%	71%
Motorcycle Time	2min8secs	1min58secs
Motorcycle Overspray	44%	57%
Motorcycle Gun Dist.	10-11 inches	12-14 inches (bottom) 4-9 inches (top)

Table 4. The third experiment. Two shapes were painted by both an expert painter and a novice, and their performance recorded.

of three tests. In all three experiments, each participant was allowed as much time as they wanted to familiarize themselves with the virtual environment, and they were allowed to paint a few test objects before starting the actual experiment. Tests were limited to only a few professional painter participants, as getting enough professional painters for a full statistical study was infeasible. These tests do, however, provide basic verification that the system performs in a similar manner to real spray painting.

The purpose of the first test was to confirm that an expert spray job on a simple flat panel is similar in both time and technique regardless of whether the painter is using the virtual system or spray painting with real paint. To begin the experiment, an expert spray painter was tracked painting a 25x40 inch panel with real paint at a spray paint facility. Then, expert and novice spray painters were tracked painting the same panel using the system (neither painter was the expert who applied the real paint job to the panel).

Table 2 summarizes the results of this test. Both expert painters painted the object in a very similar manner. The virtual spray painter took only slightly longer with a couple less passes, likely due to his gun tip being a bit further from the panel than that of the expert using real paint (which also accounts for fewer passes being made). In addition, both expert spray painters outperformed the novice spray painter.

In the second experiment, the parameters of the virtual spray gun (air/paint paint pressure, and flow rate) were adjusted so that they were different from the nominal settings. Two spray painters (who both had some knowledge of how to

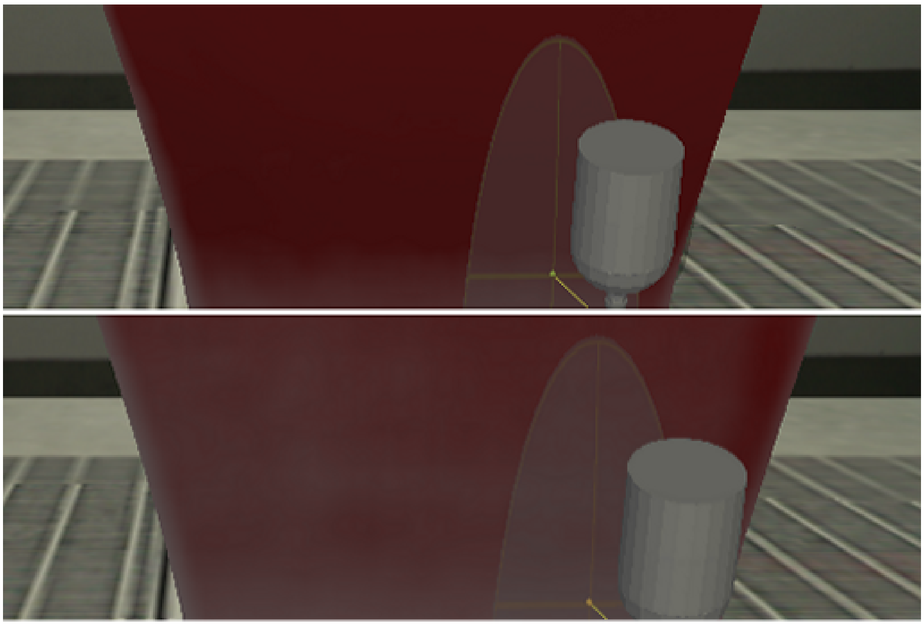

Fig. 4. Top: An image of a spray object painted with a pre-generated replay. Bottom: The same object painted with the same replay data, but with 75 cstk lower viscosity as well as 0.8 higher A/P ratio. The result is that the object is insufficiently painted due to the higher overspray caused by the parameter changes.

correctly set up a spray gun) were asked to adjust the virtual gun back to the original settings, using only the performance of the virtual gun on the surface of the panel as a guide. The painters made alterations to the gun settings by asking the experimenter to make adjustments to the gun (for instance, "lower flow rate by 15%"). The painters themselves couldn't see the current settings. Each adjustment session ended when the painter felt that the gun was "approximately" the same as its original settings.

Table 3 summarizes the results of this test: both painters were quite accurate in diagnosing what parameters had changed in the gun and in adjusting the virtual gun back to its original settings. This demonstrates that the alterations made to the spray gun settings in the virtual simulation were accurate enough to allow spray painters to properly evaluate and adjust the virtual spray gun just as they would a real gun.

In the final experiment, an expert spray painter's performance using the virtual system was compared to that of a novice spray painter. After familiarizing themselves with the virtual spray system, each was asked to paint two objects: a car hood and a motorcycle midsection. Spray time, distance from spray gun to the object, percentage of correct coverage, time, and overspray were all calculated. Each painter was asked to paint the object as completely as possible.

Table 4 summarizes the results of this test. As expected, the expert spray painter performed significantly better than the novice, showing that someone more skilled as a real spray painter performs better using the virtual system as well. Of particular note is that the expert was able to perform a rapid, almost flawless paint job using the virtual system after familiarizing himself for around a half hour with the system.

In addition to controlled testing, the system has been shown to a number of auto refinish and paint companies since its creation. User feedback was positive. A manufacturing company included the system into their training program, with positive results. After the system was introduced to the painters, they have reported reduced error levels and rejection of paint jobs. In addition, use of the system during painter training improved skill acquisition.

6 Conclusions

This paper has presented a spray paint simulation system. The primary purpose of this system is to train spray painters to use different paints and spray guns without wasting valuable paint. At the same time, the system gives very specific and helpful feedback about their performance. In addition to training spray painters, the system can also be used to evaluate the properties of new paint formulas without the need to actually manufacture the paint. Finally, user testing has been employed to verify the system's usefulness as a training tool.

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