Development and Application of a Description-based Interface for 3D Object Reconstruction

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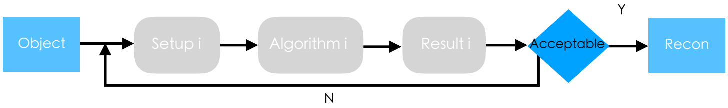
Motivation: traditional 3D Reconstruction

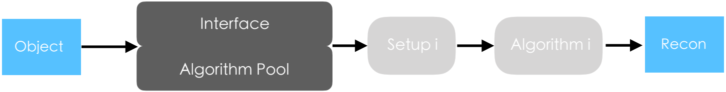


Challenges:

- Hardware: controlled environment, calibration
- Algorithms: vision background
- Results: keep trying until an acceptable result

Motivation: interface to 3D Reconstruction

What if we can create an interface above the 3D algorithms, which can select an appropriate algorithm based on users' description, and achieve a successful reconstruction result.



Contribution

Development of an interface for 3D reconstruction problem, which hides algorithmic details and allows users to describe conditions surrounding the problem. This description can be interpreteded so that an appropriate algorithm is chosen to obtain a successful reconstruction result.

Contribution (cont'd)

This contribution is significant because:

- No single algorithm can work for a diverse categories of objects. The interface, to some extent, can cover a wider range of object categories by incorporating multiple algorithms.
- An description is provides that hides the algorithmic details, thus understanding of the algorithm, or conditions to apply a specific algorithm is not a prerequisite.

Related Work: softwares

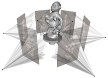
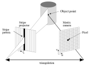
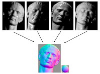
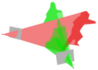
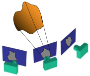
Some noteable examples of open source or commercial softwares:

Case	Software	Example	Problem
General VL	OpenCV	Mat findHomography();	Generic APIs
Software bundles	SfM + MVS	 	Cater to specific objects

Challenge

Not that we don't have enough tools, but the barrier to take advantage of these tools is high.

Related Work: algorithms

Category	Method	Problem
Shape from Stereo		Texture, Specular
		Albedo, Specular
Shape from Intensity		Albedo, Specular, Geomtry
		Albedo, Geoemtry
Shape from Silhouette		Geoemtry
		Geoemtry

Related Work: algorithms

Challenges

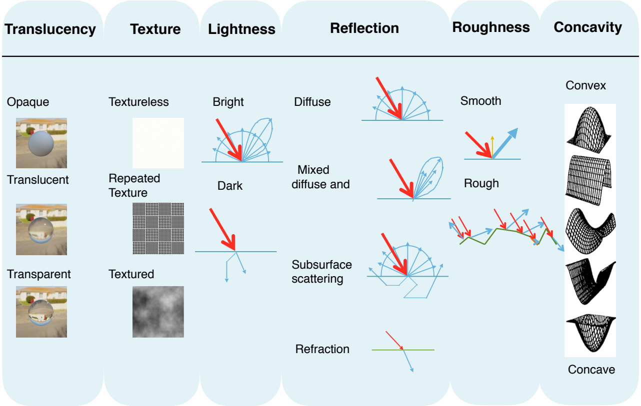
1. No algorithm works for objects with diverse properties;
2. The knowledge of whether an algorithm works is not known a priori.

Roadmap

- Taxonomy: understand the problem space;
- Description: describe the problem space;
- Mapping: discover the connection between a sub-volume in problem space to algorithm.

Taxonomy: properties of problem space

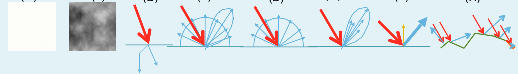
- *algorithm-centered* taxonomy categorizes algorithms based on algorithmic details, as discussed in **Related Work**;
- *object-centered* taxonomy categorizes algorithms based on the problem conditions that the algorithm can reliably works under.



Taxonomy: problem conditions

Assumptions:

- Active methods require high surface albedo (bright), in order to demonstrate the effectiveness of these methods, we focus on bright surfaces only.
- Diffuse is caused solely by surface roughness since sub-surface scattering is ignored.



Texture		Lightness		Reflection		Roughness		Label	Class
Textureless (TI)	Textured (T)	Dark (D)	Bright (B)	Diffuse (D)	Mixed (M)	Smooth (S)	Rough (R)		
Yes			Yes	Yes			Yes	TI-B-D-R	1
Yes			Yes		Yes	Yes		TI-B-M-S	2
	Yes		Yes	Yes			Yes	T-B-D-R	3
	Yes		Yes		Yes	Yes		T-B-M-S	4

Description: model and representations

Model	**Representation**
Texture	*Texture randomness*
Lightness	*Albedo*
Specularity	*Specular/diffuse ratio*
Roughness	*SD of facet slopes*

Table: Representations of the 3D reconstruction problem.

Description: expression

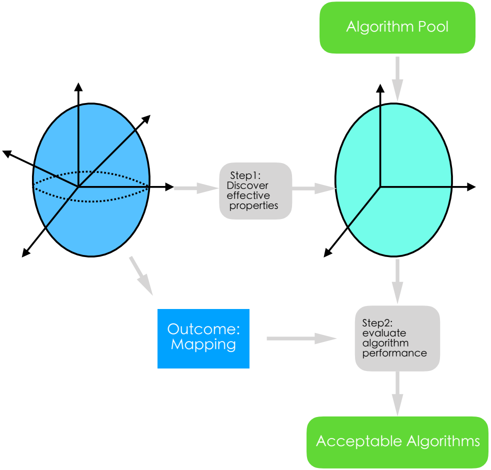
We use three discrete scales to parameterize these properties: *low* (0.2), *medium* (0.5), and *high* (0.8).

Object	Texture	Albedo	Specular	Rough	**Label**
Class 1	low/med	high	low/med	high	Tl-B-D-R
Class 2	low/med	high	high	low/med	Tl-B-M-S
Class 3	high	high	low/med	high	T-B-D-R
Class 4	high	high	high	low/med	T-B-M-S
Class 5	high	low/med	low/med	high	T-D-D-R
Class 6	high	low/med	high	low/med	T-D-M-S

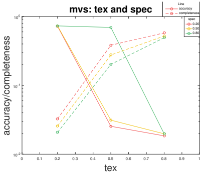
Table: Expression of the reconstruction problem for the object classss.

Mapping

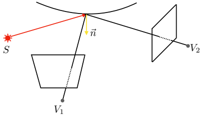
Investigate the problem conditions under which the algorithms can reliably work. This strucure of this chapter is as follows



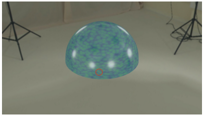
Mapping: notable findings 1



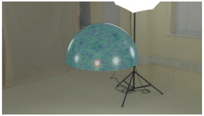
(a). Algo. performance



(b) Image formation



(c) V_1



(d) V_2

Figure: (a) shows the algorithm performance w.r.t. texture and specularity. (b) shows the reflection of light off a specular surface. V_1 received the diffuse component while V_2 receives the specular component. (c), (d) shows the images observed from these two views. The specular area (red circle) observed in V_2 is visible in V_1.

Mapping: notable findings 2

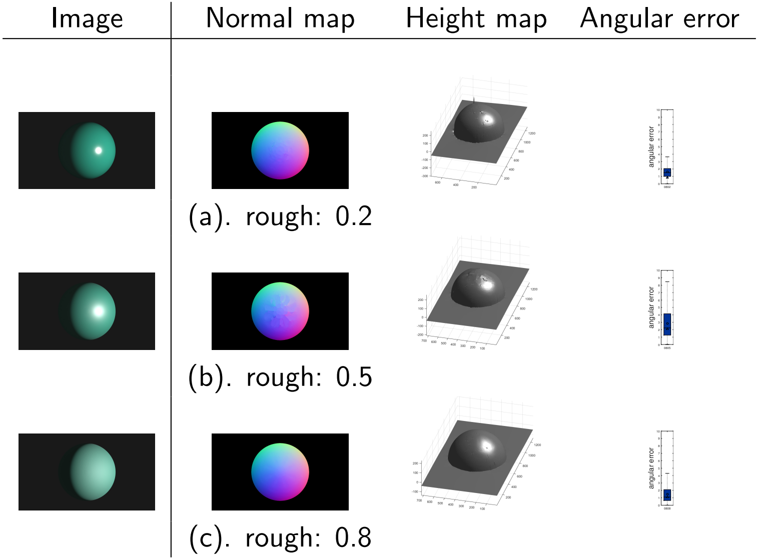
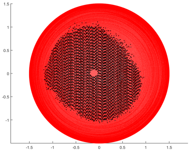
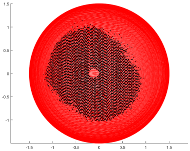


Figure: The effect of roughness on PS. Albedo is set as 0.8, and specular is set as 0.8. (b) demonstrates that a medium level roughness would lead to worse normal

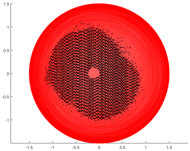
Mapping: notable findings 3



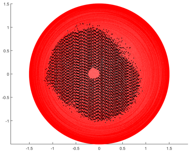
(a) specular: 0.2



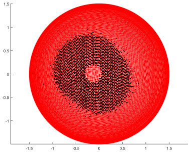
(b) specular: 0.5



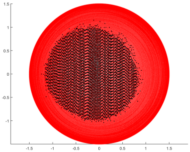
(c) specular: 0.8



(d) roughness: 0.2



(e) roughness: 0.5



(f) roughness: 0.8

Figure: (a)-(c): the roughness is set as 0.2, and specular has a negative effect on completeness; (d)-(e): the specular is set as 0.8, roughness has a positive effect on completeness.

Conclusions

- PMVS can work on specular surfaces;
- EPS and GSL fails on highly specular areas, and a blurred specular area causes worse results.

Interpretation: Key Evaluation Questions

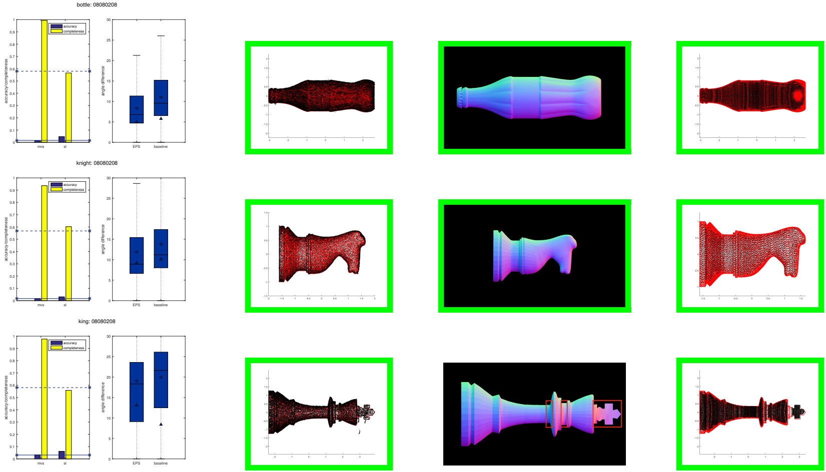
- Evaluation of mapping: is the mapping robust to changes of shape?
- Evaluation of interpreter: can the proof-of-concept interpreter return a successful reconstruction given the correct description?

Interpretation: evaluation of mapping

- Shape variation: too vast and complicated to model;
- Instead focus on one geometric property: surface concavity, and see how robust is the mapping with respect to concavity changes.

Interpretation: evaluation of mapping (cont'd)

Quantitative results	Qualitative results



PMVS EPS GSL

Figure: Problem condition: 08080208, mapped algorithms: PMVS, EPS, GSL.

Interpretation: evaluation of mapping (cont'd)

Conclusion:

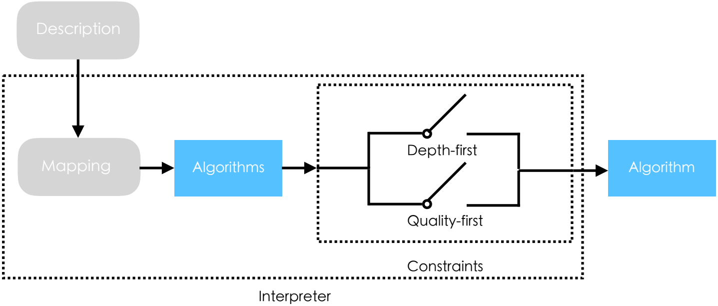
- Mappings to PMVS and GSL are robust to concavity changes whereas those to EPS are not.

Suggestions:

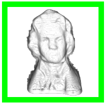
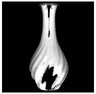
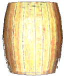
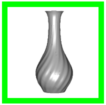
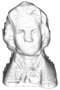
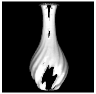
- Develop more advanced description, incorporating concavity into the description
- Use more underlying algorithms that are robust to concavity changes.

Proof-of-concept interpreter

An interpreter selects an appropriate algorithm based on description of problem condition and constraints.



Interpretation: evaluation of interpreter

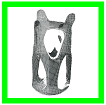
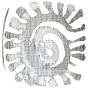
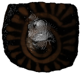
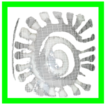
Desc #	Bust	Vase1	Barrel	Vase0	Selected Algo.
1					GSL
2					EPS
3					GSL
4					PMVS

Interpretation: real-world objects

class #	1	2	3&4	5&6
description	textureless diffuse bright	textureless mixed d/s bright	textured diffuse dark/bright	textured mixed d/s dark/bright
object				

Figure: The rerepsentatives of the six classes of objects used for evaluation.

Interpretation: evaluation of interpreter (cont'd)

Desc #	Statue	Cup	Pot	Vase	Selected Algo.
1					GSL
2					EPS
3					GSL
4					PMVS

Conclusions

- the proposed description is able to give correct reconstruction for non-concave objects
- To deal with more complicated objects, we need more complicated properties, or ways to describe the objects, but the challenge is the easy mathematical representation might not be available.
- Using the simple descriptive language and proof-of-concept interpreter, we demonstrate the possibility of using descriptive properties to hide algorithmic details.

Take-away message

Computer vision should focus on more than just algorithms, but easier accessibility.

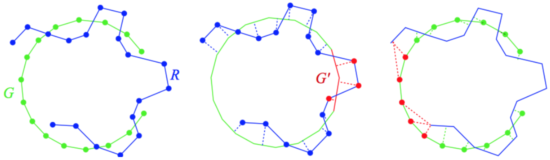
Mapping: algorithms and baseline

Technique	Texture	Albedeo	Specular	Roughness
PMVS: patch-based, seed points propagation MVS.	High	-	Low	-
EPS: example-based Photometric Stereo	-	High	Low	High
GSL: Gray-code Structured Light technique	-	High	Low	High
VH: volumetric Visual Hull.	-	-	-	-
LLS-PS: linear least squares Photometric Stereo.	-	High	Low	High

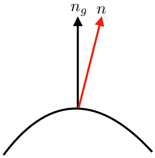
Table: Summary of the selected and baseline algorithms.

Mapping: quantitative measures and criteria

- accuracy: the distance d such that $X\%$ of the points on R are within distance d of G is considered as accuracy;
- completeness: the percentage of G that is reconstructed by R;
- angular error: angle between the estimated and ground truth normal, *i.e.*, $arccos(n_g^T n)$.



Accuracy and completeness



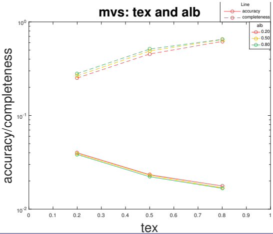
angular error

Mapping: EPD of PMVS

Table: Problem conditions for establishing the *effective problem domain* of PMVS.

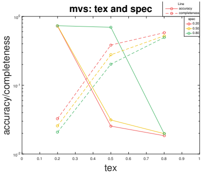
Cond	Texture	Albedo	Specular	Roughness
(a)	[0.2, 0.8]	[0.2, 0.8]	0.0	0.0
(b)	[0.2, 0.8]	0.8	[0.2, 0.8]	0.0
(c)	[0.2, 0.8]	0.8	0.0	[0.2, 0.8]
(d)	0.8	[0.2, 0.8]	[0.2, 0.8]	0.0
(e)	0.8	[0.2, 0.8]	0.0	[0.2, 0.8]
(f)	0.8	0.8	[0.2, 0.8]	[0.2, 0.8]

Cond. (a). Texture and Albedo

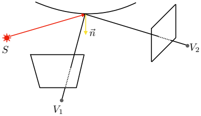


Mapping: EPD of PMVS (cont'd)

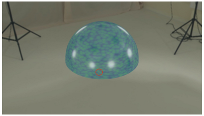
Cond. (b). Texture and Specularity



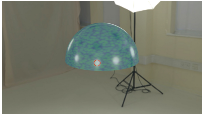
(a). Algo. performance



(b) Image formation



(c) V_1

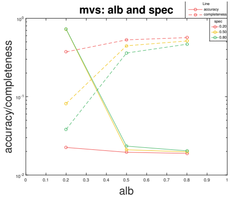


(d) V_2

Figure: (a) shows the algorithm performance w.r.t. texture and specularity. (b) shows the reflection of light off a specular surface. V_1 received the diffuse component while V_2 receives the specular component. (c), (d) shows the images observed from these two views. The specular area (red circle) observed in V_2 is visible in V_1.

Mapping: EPD of PMVS (cont'd)

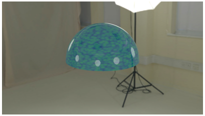
Cond. (d). Albedo and Specularity



(a) spec: 0.2

(b) spec: 0.8

(c) alb: 0.2



(d) alb: 0.8

Figure: The law of conservation of energy demands that as the specular reflection increases, the diffuse reflection decreases.

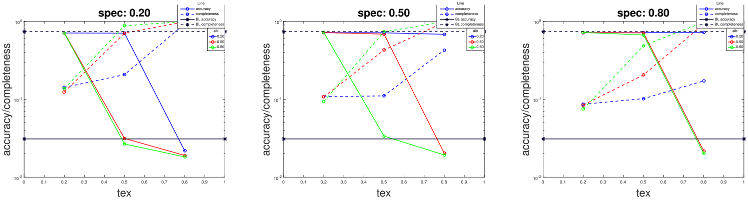
Mapping: *effective properties* of PMVS

Metric	Texture	Albedo	Specular	Roughness
Accuracy	✓	✓	✓	✗
Completeness	✓	✓	✓	✗

Table: The *effective problem domain* of PMVS in terms of accuracy and completeness.

Mapping: mapping construction

- Accuracy and completeness improves consistently as the *texture* level increases.
- Accuracy and completeness results deteriorate consistently as *specularity* increases, and this negative impact is most significant when texture level is medium or albedo value is low.
- The effect of *albedo* on a surface with low texture is negligible. However, albedo has a noticeably more significant positive impact on completeness as the texture of a specular surface increases.



Mapping: mapping construction (cont'd)

Metric	Texture	Albedo	Specular	Roughness
Accuracy	0.5	0.5	0.2	-
&Completeness	0.5	0.8	0.2	-
	0.5	0.8	0.5	-
	0.8	0.2	0.2	-
	0.8	0.5	0.2	-
	0.8	0.8	0.2	-
	0.8	0.5	0.5	-
	0.8	0.8	0.5	-
	0.8	0.5	0.8	-
	0.8	0.8	0.8	-

Table: The working problem conditions of PMVS in terms of the two metrics *accuracy* and *completeness*.