

Soil Endoscope for Sub-Surface Irrigation Uniformity Testing

2018 Final Report

Research Agreement No. M1603138

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Introduction

The overall goal of this project was to build a soil probe that could conveniently measure sub-surface irrigation uniformity. This phenomenon is illustrated in the following figure. Figure 1 (from the original proposal) shows a soil profile colored with the fluorescent dye Uranine (Gerke, Mallants, and Sidle 2013¹). Most fluorescent dyes respond when exposed to ultraviolet light. Uranine, in particular, will respond to shortwave UV light.

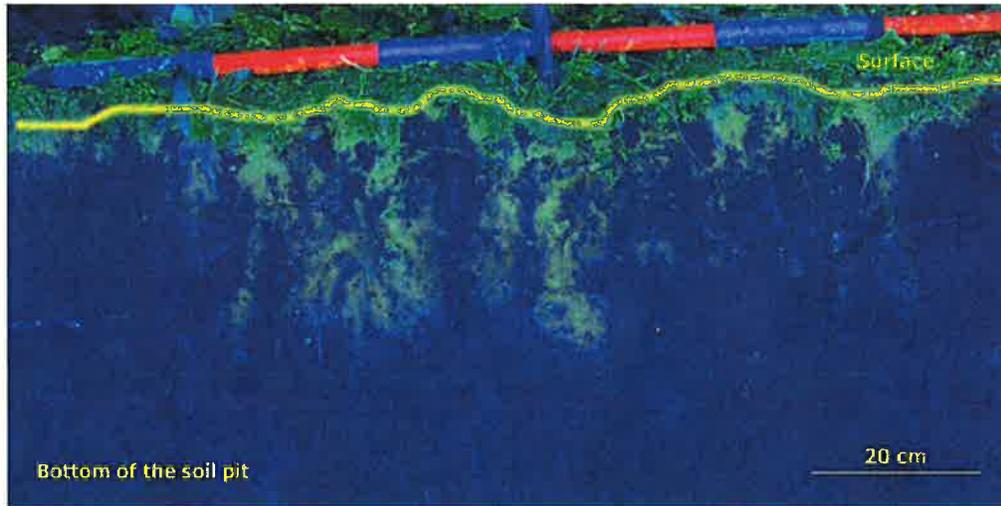


Figure 1 Soil profile colored with fluorescent dye

Objectives

This project had four objectives:

1. Design and build two prototype soil endoscopes.
2. Laboratory testing of three types of fluorescent dyes to determine optimal concentration and camera calibration.
3. Field test the soil endoscope at the AgriLife research farm in Bushland, TX.
4. Field test the endoscope in at least three locations in the Panhandle region

As will be explained, not all of the project objectives were met.

¹ Gerke, K.M., D. Mallants, and R.C. Sidle. 2013. "Criteria for Selecting Fluorescent Dye Tracers for Soil Hydrological Applications Using Uranine as an Example." *Journal of Hydrology and Hydromechanics* 61 (4): 313–25. doi:10.2478/johh-2013-0040.

System Design

The basic design of the probe is relatively simple. A small and inexpensive camera is mounted inside a stainless steel tube. A small mirror reflects the image through a port on the side of the probe.

Additionally, a small UV lamp is placed below the mirror pointed at the port. A piece of glass tubing separates the outside of probe from the camera and mirror inside. The end of the tube is capped with a pointed tip. The probe head is attached to a long tube, and the camera's cable is threaded through the tube. At the end of the rod, a cap is attached to the tube. A slot on the side of the cap allows access to the camera cable.

Figure 2 illustrates the original design of the probe. Appendix A contains detailed technical drawings of each probe component. Figures 3, 4, 5, and 6 show the probe prototype as built. Figure 6 shows a disassembled view of the probe head.

Appendix B shows the R code used to process the captured video and process it into a composite image.

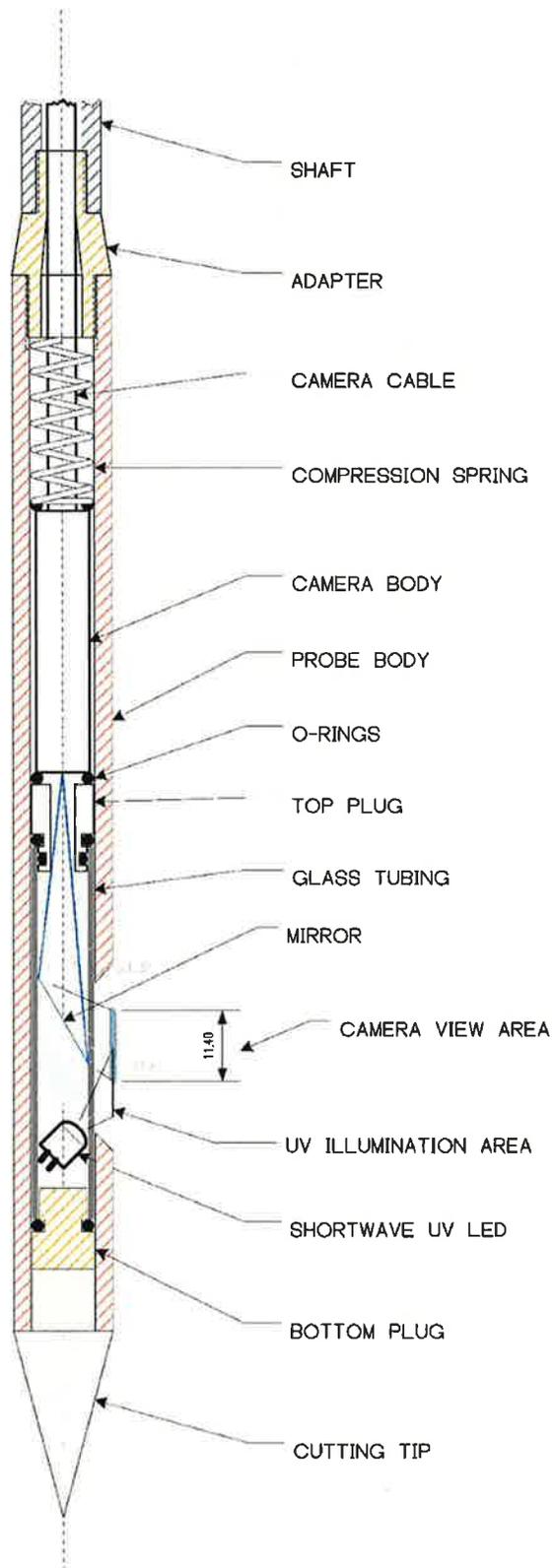


Figure 2 Schematic view of probe head, as originally designed

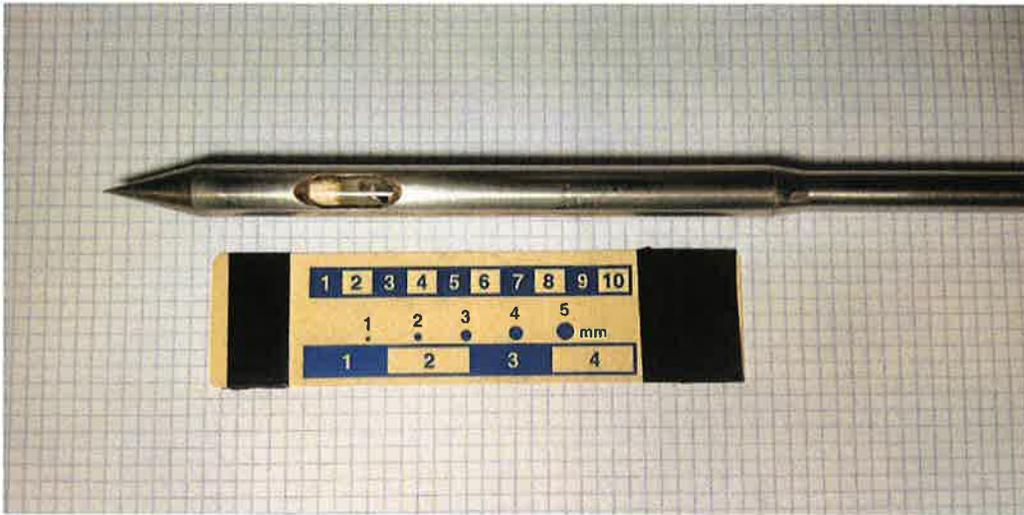


Figure 3 Probe head, assembled and attached to rod



Figure 4 Probe cap with SDS+ adapter

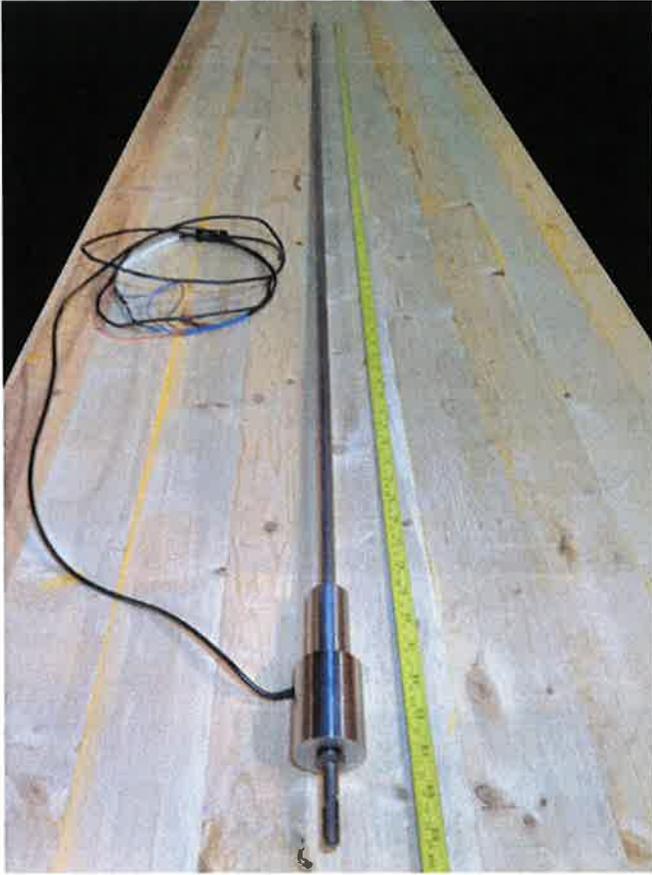


Figure 5 fully assembled probe - overall length 86 in.



Figure 6 Disassembled view of the probe head.

Project Progress and Problems

This project experienced multiple problems that prevented achieving most of the objectives. The problems we have to be roughly divided into fabrication problems, camera failures, and operational problems. Each of these problems is described below.

Fabrication Costs

The fabrication cost was the most significant problem for this project. The original cost estimates for fabricating probe prototypes were based on informal conversations with a machinist from out-of-state. Once the measured drawings were delivered to the machinists at Amarillo returned significantly higher cost estimate was returned. The original cost estimate for fabricating the prototypes is approximately \$700 the initial cost estimate for fabricating the first prototype was approximately \$2500. Several design changes were made were necessary to reduce the cost of fabrication. However, these design changes required hand-fabricating several of the components that held the cameras in place. This hand fabrication process was incredibly tedious and created and delays in the project. Ultimately, only one prototype could be fabricated because of the increased costs.

For the first prototype, we chose to use the larger of the two camera types. The 8.5 mm camera had better video quality and had their potential to produce more usable images. The disadvantage with this camera, however, is that it required a larger probe body. The prototype currently has a diameter of approximately 16 MM. As will be described in the operational problems section, this larger probe body proved to be too difficult to insert into the soil reliably.

Dimensional uncertainty

Another problem that caused some significant delays was a dimensional uncertainty associated with the cameras. These cameras are relatively inexpensive however the suppliers rarely make more than one production run. Typically, a manufacturer will change their designs slightly with each production run. The consequence of this is that we could not assume exact dimensions of the camera body, cable, or attachments. The only way to be sure of the dimensions of the camera was to order one and measure it.

Probe window

The probe window was initially designed to use sapphire glass. Sapphire glass is known for being extremely strong and transparent to shortwave ultraviolet light. These two features are critical and the design of the probe. A significant force would be required to drive the probe into the soil. Sapphire glass had the best potential to withstand the forces in flexing of the probe body. Sapphire glass tubing is also used as a sample container in Nuclear Magnetic Resonance Spectroscopy and is available in a standard size of 10 mm diameter. This was convenient for the project since the probe body was approximately 10 mm on the inside. The problem, however, was that the sample containers are not an ideal length and would need to be cut to an appropriate length. Finding someone with the tools and experience to cut sapphire glass proved to be extremely difficult the only supplier we could find who was willing to try cutting the tubing was in Dallas. It seemed unwise to purchase at \$700 piece of glass and send it off to an unknown person. Instead, we tried to use fused quartz instead of sapphire. Fused quartz is slightly stronger than normal glass and is mostly transparent the shortwave ultraviolet light. It

also has the advantage of being significantly less expensive. The sapphire glass tube cost approximately \$700 for a single 10cm piece and 48-inch fused quartz tube cost approximately \$10. Fused quartz is challenging to cut two, but we were able to find a supplier in Amarillo who was willing to cut the tubing. This in itself proved to be problematic since about half of the tubing was destroyed during the cutting process. Fused quartz is similar to tempered glass in that it is pre-stressed and breaks easily during cutting. We were able to obtain several pieces sufficient for this project, but this did involve modifying the design slightly to allow more space inside the probe body for flexing and bending. We also increased the thickness of the pro body to reduce flexible and bending.

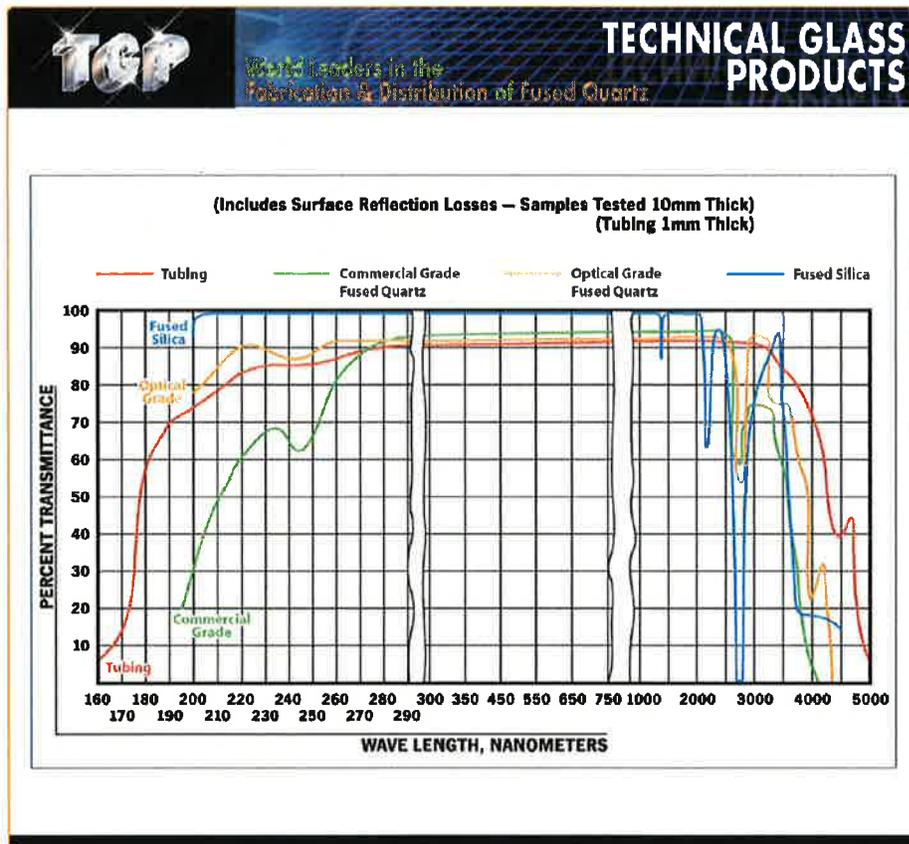


Figure 7 Fused Quartz light transmittance, as specified by the tubing supplier

Operational Problems

Several operational problems were found during preliminary testing.

Camera failures

Two sets of cameras were purchased for this project. The larger diameter cameras used a wireless connection. This offered a distinct advantage in that no cables would be connected to a tablet or phone to record video while the probe was in use. During initial testing of the probe, the larger diameter cameras failed. Part of the assembly process involves separating the camera head from the wireless transmitter. Figure 7 shows a disassembled view of both the wireless transmitter and the camera. It is

possible that vibration resulting from striking the probe with a hammer to insert the probe cost a short in the camera head. Another more likely possibility is that electrostatic discharge occurred while the probe was inserted into the ground.

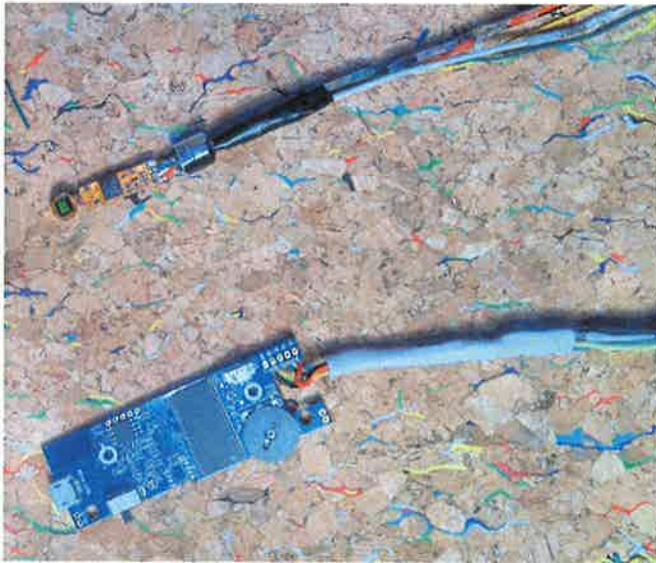


Figure 8 Disassembled camera

Failure of the large camera meant that we had to use the smaller diameter cameras as a replacement. The smaller cameras would still provide reasonable image quality but it also meant that we had to fabricate different camera mounts in order to accommodate the small camera (5.5 mm) in a body designed for the large camera (8.5 mm). Various materials were tested for fabricating the camera mounts. The challenge with this modification was that the material had to be flexible enough to absorb some of the vibration yet still hold the camera in place. Balsa wood was selected because it was the easiest to work with. An example of the camera mount is shown in Figure 6.

Soil Dye Adsorption

The original project plan called for testing three different fluorescent dyes. After consulting some MSDS references and application notes, fluorescein dye was selected. Fluorescein is a di-sodium salt that fluoresces yellow/green (512 nm) when exposed to blue or shortwave UV light. This dye is approved for environmental use and is typically used as a tracer in septic systems. Using the Pullman clay loam soil found at Bushland, we tested the dye to see how well it would show up under UV light. We found that, when the soil is wetted at or above Field Capacity, the fluorescence is easily visible with UV light and partially visible with white light. Figures 9 & 10 show undyed and dyed soil in visible and UV light. The dyed soil in visible light has a greenish coloring.

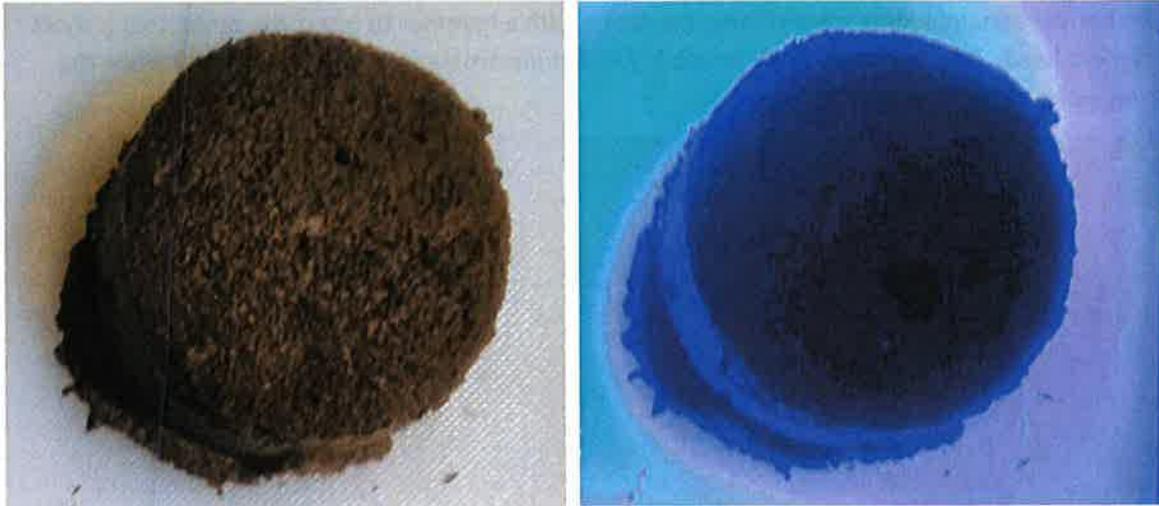


Figure 9, Left: un-dyed soil in visible light, Right: un-dyed soil in UV light

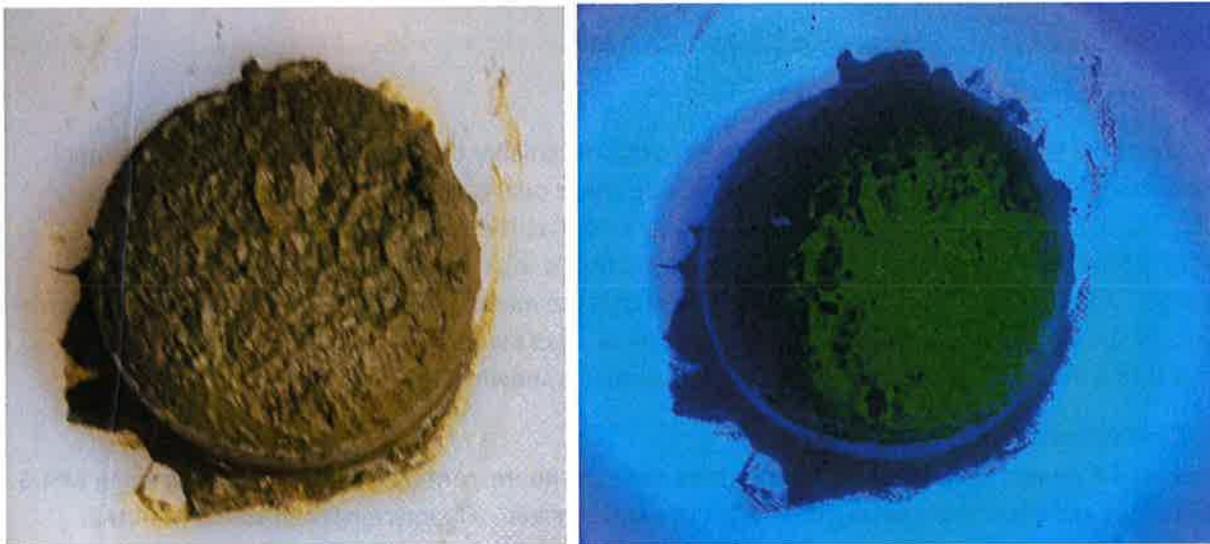


Figure 10 Left: fluorescein dyed soil in visible light, Right: fluorescein dyed soil in UV light

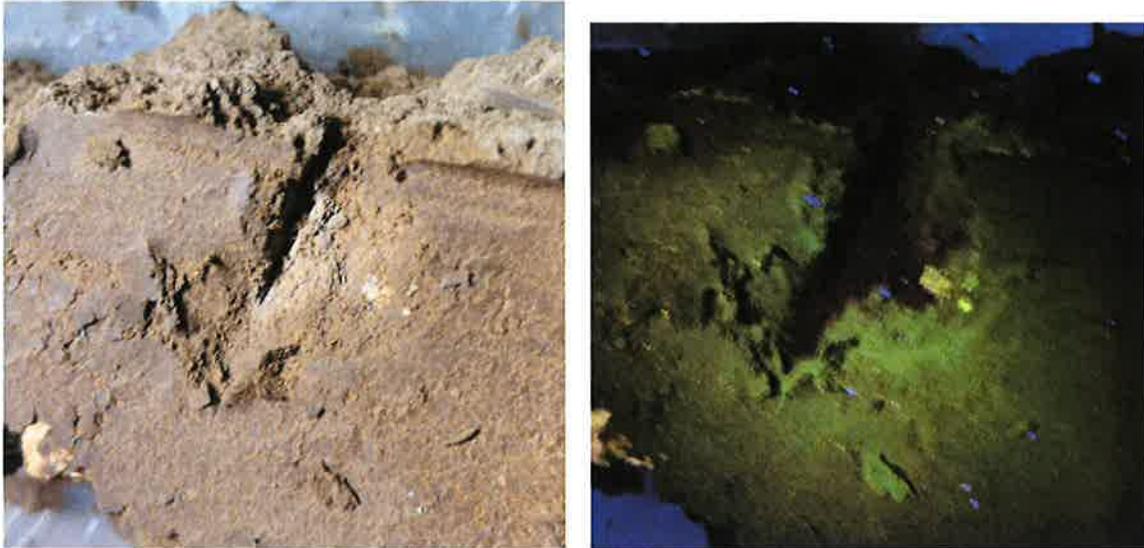


Figure 11 Partially wetted soil sample. Left: in visible light, Right: in UV light. Note that the dark area in the center is only partially wetted, but the surrounding area is near close to field capacity.

It appears that, at lower dye concentrations or moisture levels, the Fluorescein does not fluoresce. This could be because the water molecules are more tightly bound to the clay particles and the Fluorescein falls out of solution. Another possible explanation is that the Fluorescein molecules are adsorbed to the clay particles. In either case, significant amounts of both water and dye are required to produce an apparent fluorescent effect.

Insertion Force

The 16 mm diameter probe required significantly more force than expected during preliminary insertion testing. The battery operated impact hammer was utterly inadequate if the soil was even slightly dry. The only way we had any success inserting the probe was to use a small sledgehammer. The probe cap was designed to withstand this magnitude of impact force and performed as expected. The SDS+ adapter, however, did not withstand the impact. Luckily, these adapters are inexpensive enough to be disposable. The probe body performed well, and the fused quartz tubing did not break or chip during several insertions.



Figure 12 Damaged SDS+ adapter, mainly caused by frustration

Alignment/Positioning

Maintaining proper camera positioning was a constant problem during testing. The design for the large diameter camera uses a spring to hold the camera in place. This was feasible because the camera's diameter was slightly larger than the glass tubing. The fused quartz tubing was cut so that the distance between the mirror and camera was optimal for the camera's focal length. The smaller diameter cameras had a different focal length, which required manually positioning them after they were placed in the probe body. Figures 9, 10, and 11 illustrate how the camera would become misaligned during soil insertion. The extreme vibration during insertion caused the change in alignment. The only solution to this problem was to use a tighter cable fitting so that the camera could not move. However, this fitting made installation more difficult.



Figure 13 Initial camera alignment



Figure 14 Camera alignment after a few minutes of use



Figure 15 Camera alignment after several minutes of use.

Window Blockage

Perhaps the most significant problem was caused by loose soil particles blocking the probe window. This appears to be caused by a combination of loose particles and vibration from the impacts during insertion. The loose particles accumulate in-between the probe window and the displaced soil. The probe wall is thick enough (2.8 mm) that the distance between the glass tubing and displaced soil provides enough space for particles to accumulate. These particles are carried down as the probe is inserted, effectively blocking the camera's view after moving a few inches.

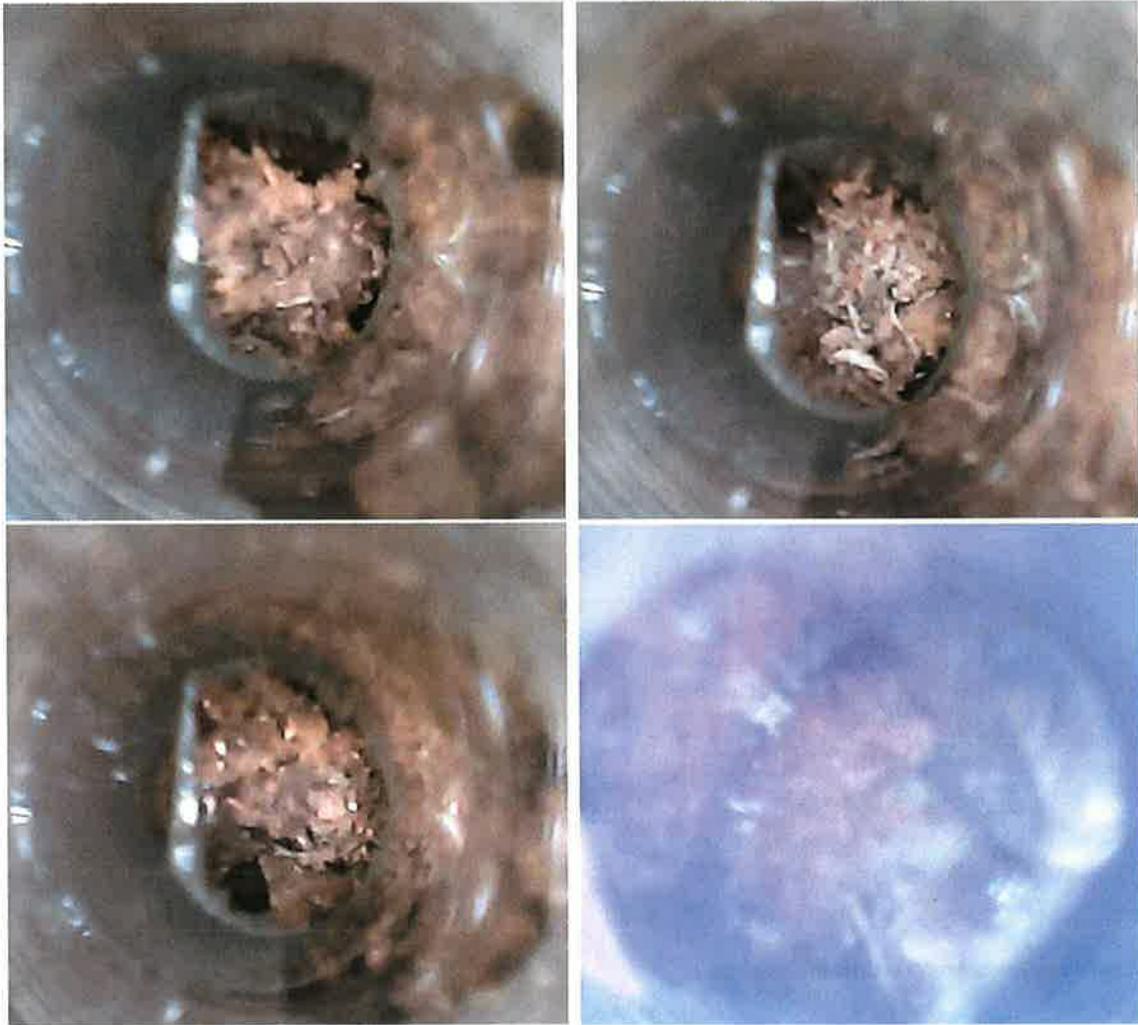


Figure 16 Examples of occluded probe window

Conclusions

Overall, this project was not successful. The issues can be summarized as follows:

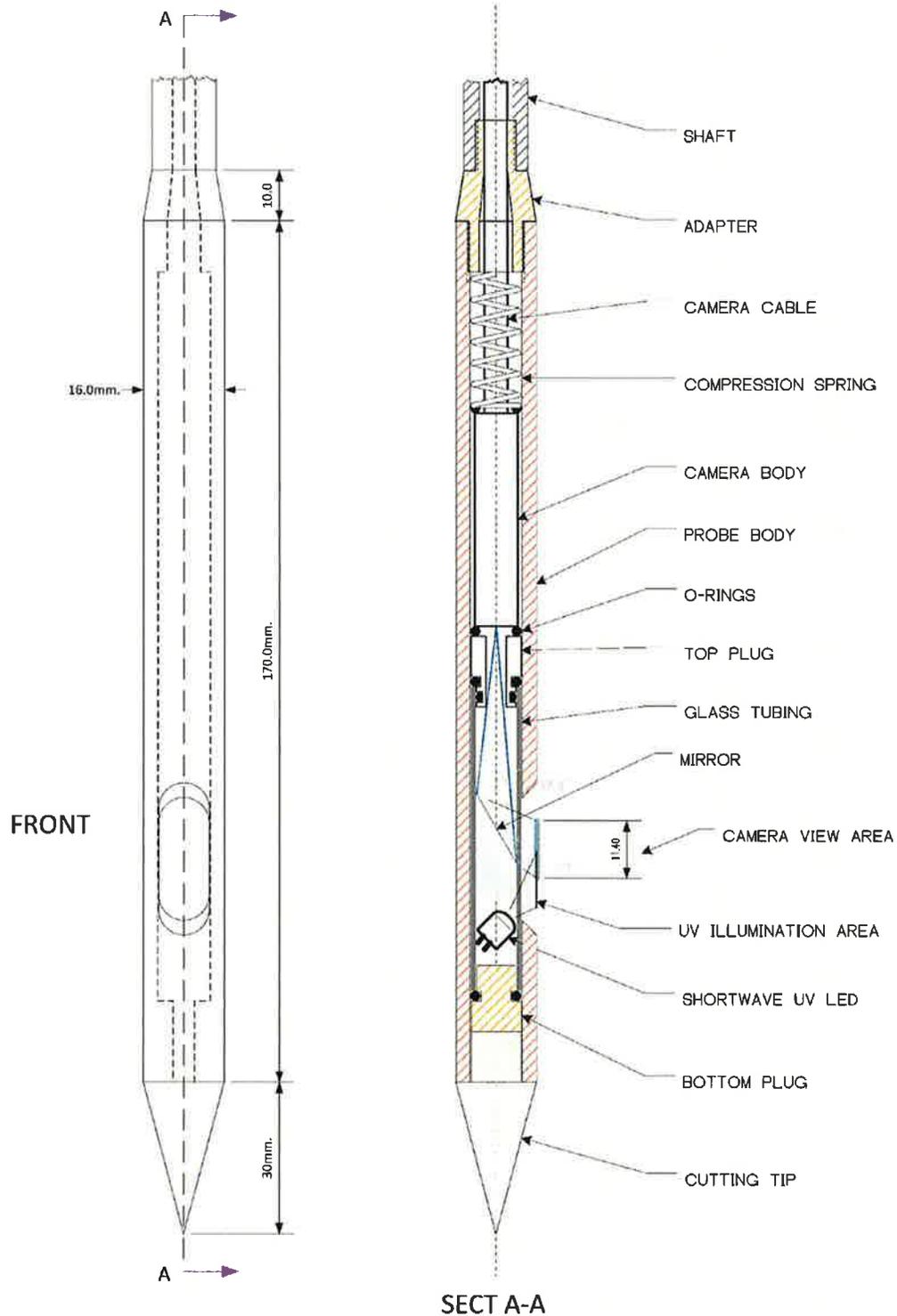
- Underestimation of fabrication costs meant that lessons learned from the first prototype could not be applied to the second prototype.
- Camera failure introduced significant delays while we determined how to mount the 5.5 mm camera in a probe designed for an 8.5 mm camera.
- The insertion force required in even slightly dry soils means that this probe has limited utility in heavy textured soils.
- Loose soil particles blocked the camera's view after only a few inches insertion, and the view remained blocked until the probe was removed entirely from the soil.

We were able to build and test one prototype probe. The video processing code was developed and tested using some rudimentary video capture. It may be possible to resolve some of the insertion force issues by using a smaller diameter probe. A thinner probe body would likely resolve the window blockage issue, but this is only speculation. While the initial theory of this project still seems valid, the problems we encountered prevented any real testing of the theory.

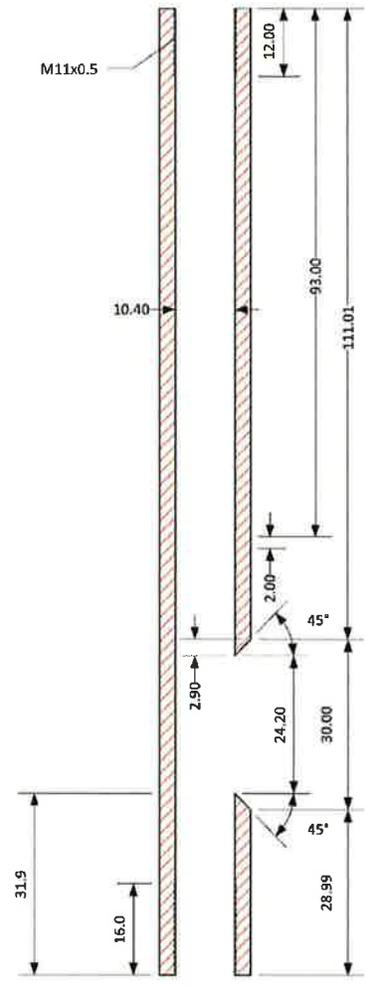
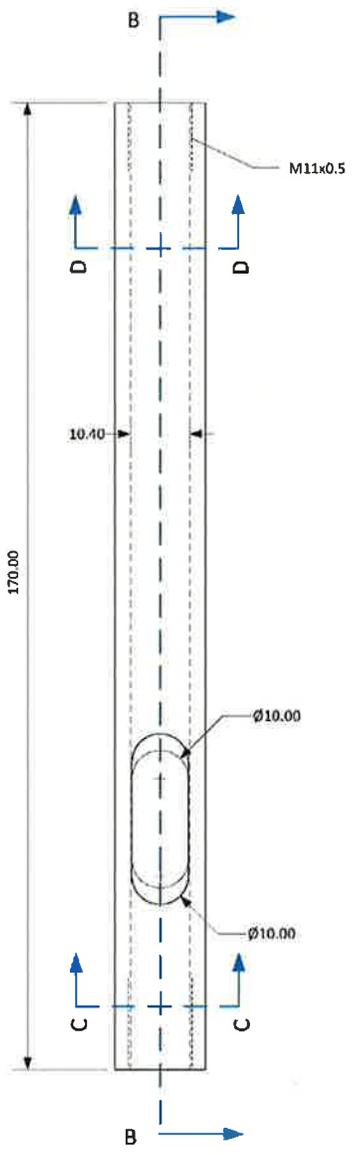
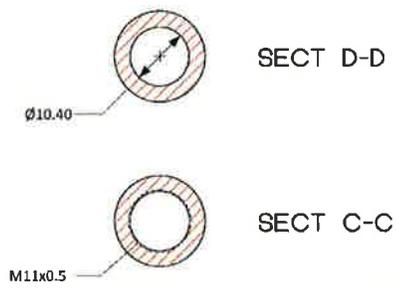
Appendix A: Technical Drawings

The following figures are technical drawings of each of the probe components. The last figure is a design check to verify that the probe window was visible through the camera and that there was sufficient overlap between the UV lamp and the camera's field of view. These are the figures as they were delivered to the machinist in Amarillo.

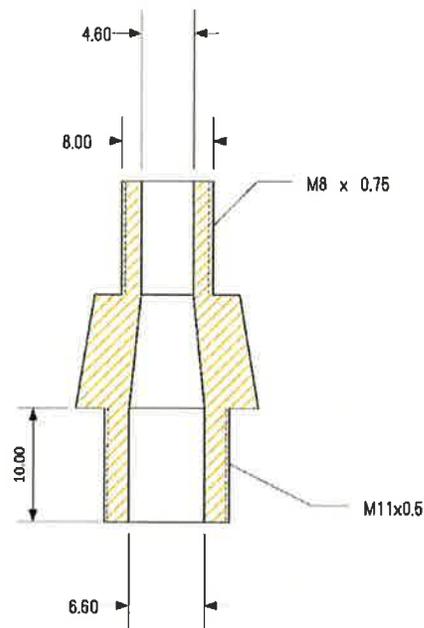
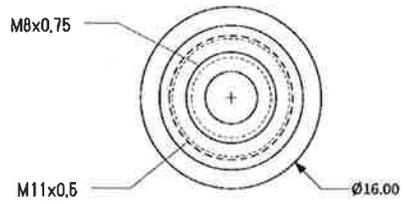
ITEM	QTY.	
Probe Body	1	
Adapter	1	
Cutting Tip	1	



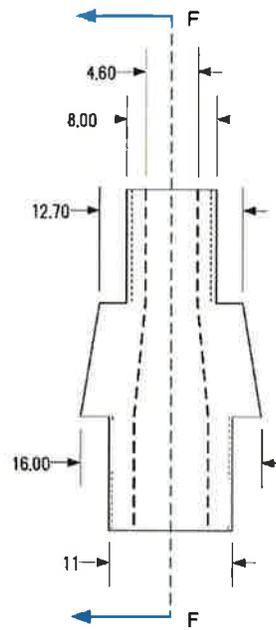
TITLE		DESCRIPTION			
SOIL PROBE ASSEMBLY, ANNOTATED		FULLY ASSEMBLED PROBE. *NOTE: ONLY ITEMS IN PARTS LIST ARE REQUESTED			
DRAWN BY CHARLES HILLYER		Texas A&M AgrLife Research 6500 Amarillo Blvd W Amarillo, TX, 79106			
FILENAME ENDSCOPE 18.VSDX	SCALE 1:1	PAGE 1 OF 9	DRAWING NO. 2	DATE 2/12/2018	



TITLE	SOIL PROBE BODY		DESCRIPTION	Texas A&M AgriLife Research 6500 Amarillo Blvd W Amarillo, TX, 79106
DRAWN BY	CHARLES HILLYER		MATERIAL	
FILENAME	ENDOSCOPE 18,VSDX		304 SS	
SCALE		PAGE		ALL DIMENSIONS IN MILLIMETERS
1: 1		2 OF 9		DRAWING NO.
				DATE
				2
				2/12/2018

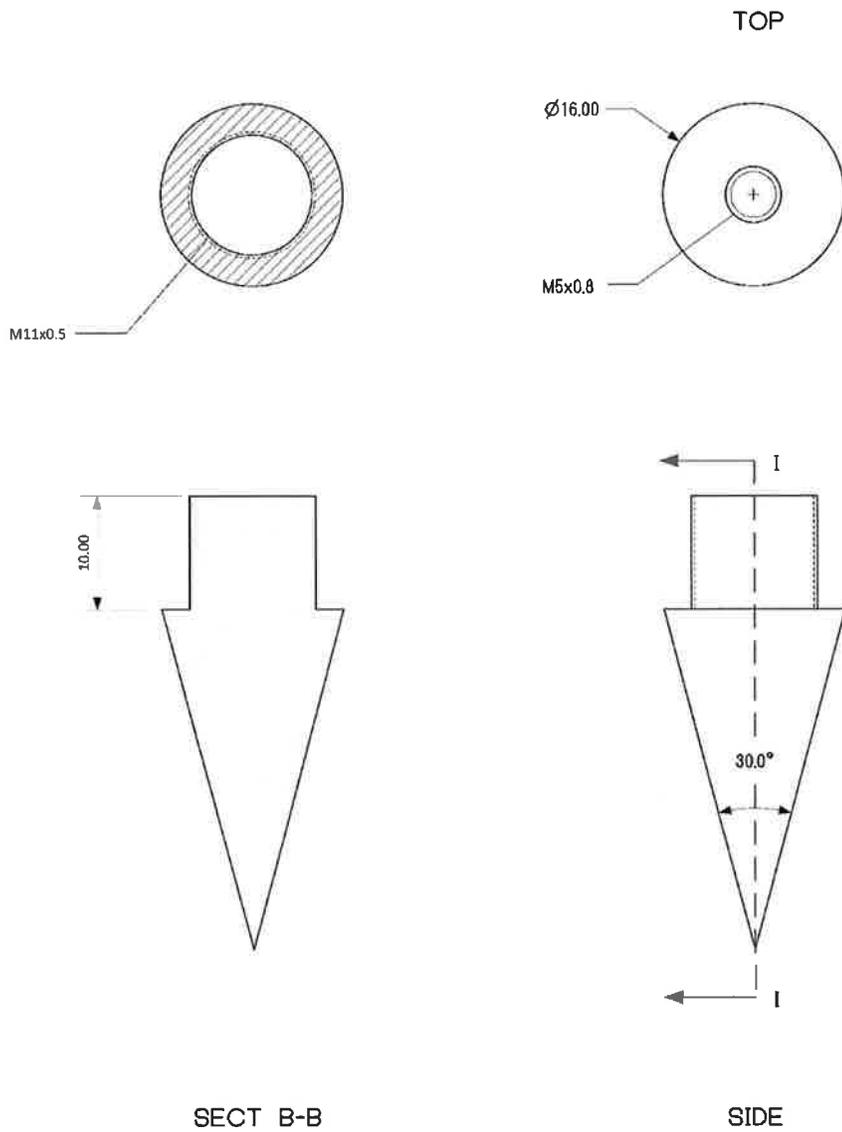


SECT F-F



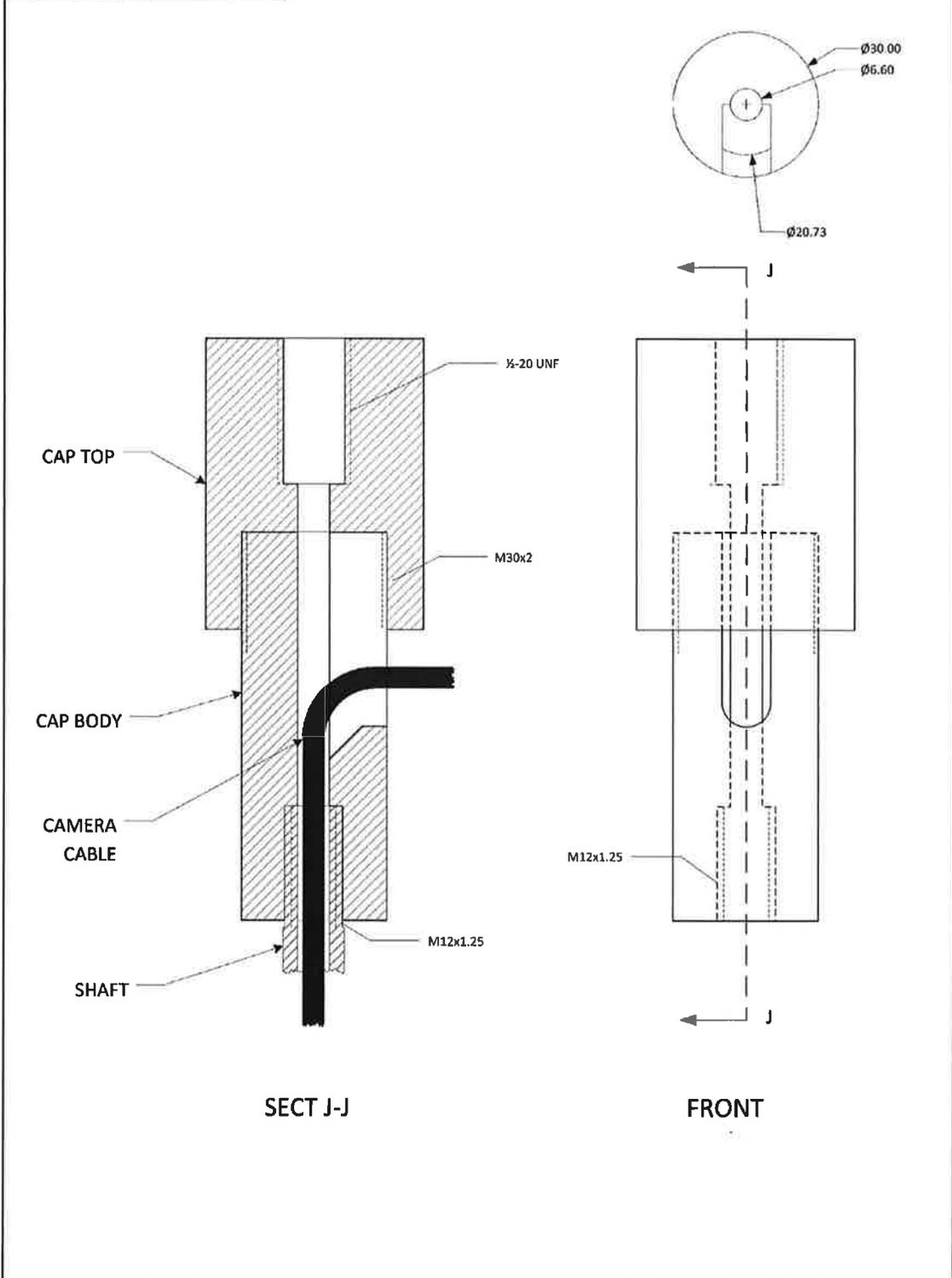
FRONT

TITLE ADAPTER		DESCRIPTION				Texas A&M AgriLife Research 6500 Amarillo Blvd W Amarillo, TX, 79106
DRAWN BY CHARLES HILLYER		MATERIAL 304 SS		ALL DIMENSIONS IN MILLIMETERS		
FILENAME ENDOSCOPE 18.VSDX		SCALE 2: 1	PAGE 3 OF 9	DRAWING NO. 2	DATE 2/12/2018	

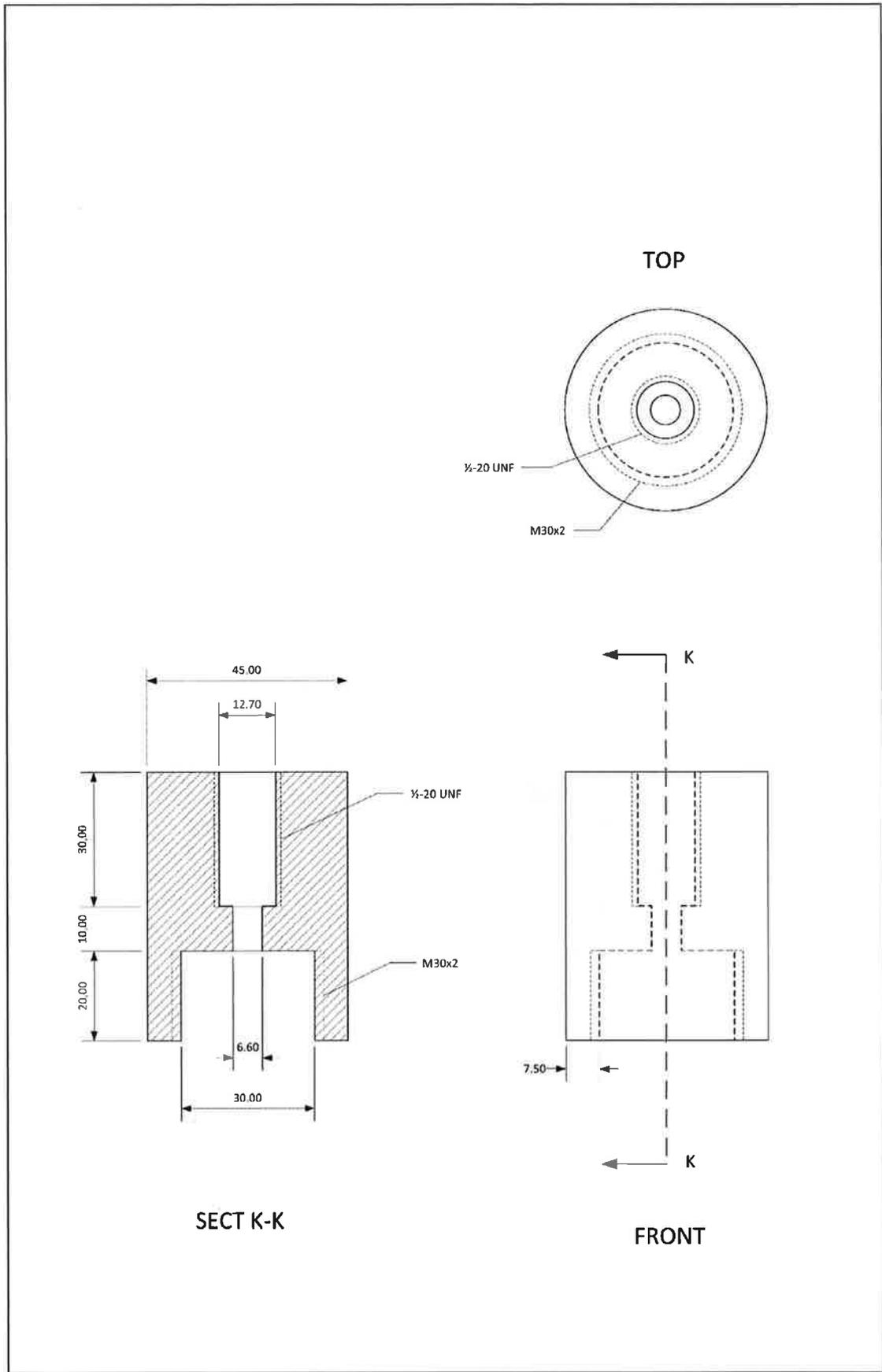


TITLE		DESCRIPTION			Texas A&M AgriLife Research 6500 Amarillo Blvd W Amarillo, TX, 79106	
SOIL PROBE BODY		MATERIAL	ALL DIMENSIONS IN MILLIMETERS			
DRAWN BY		304 SS				
CHARLES HILLYER		SCALE	PAGE	DRAWING NO.	DATE	
FILENAME		2: 1	4 OF 9	2	2/12/2018	
ENDOSCOPE 18.VSDX						

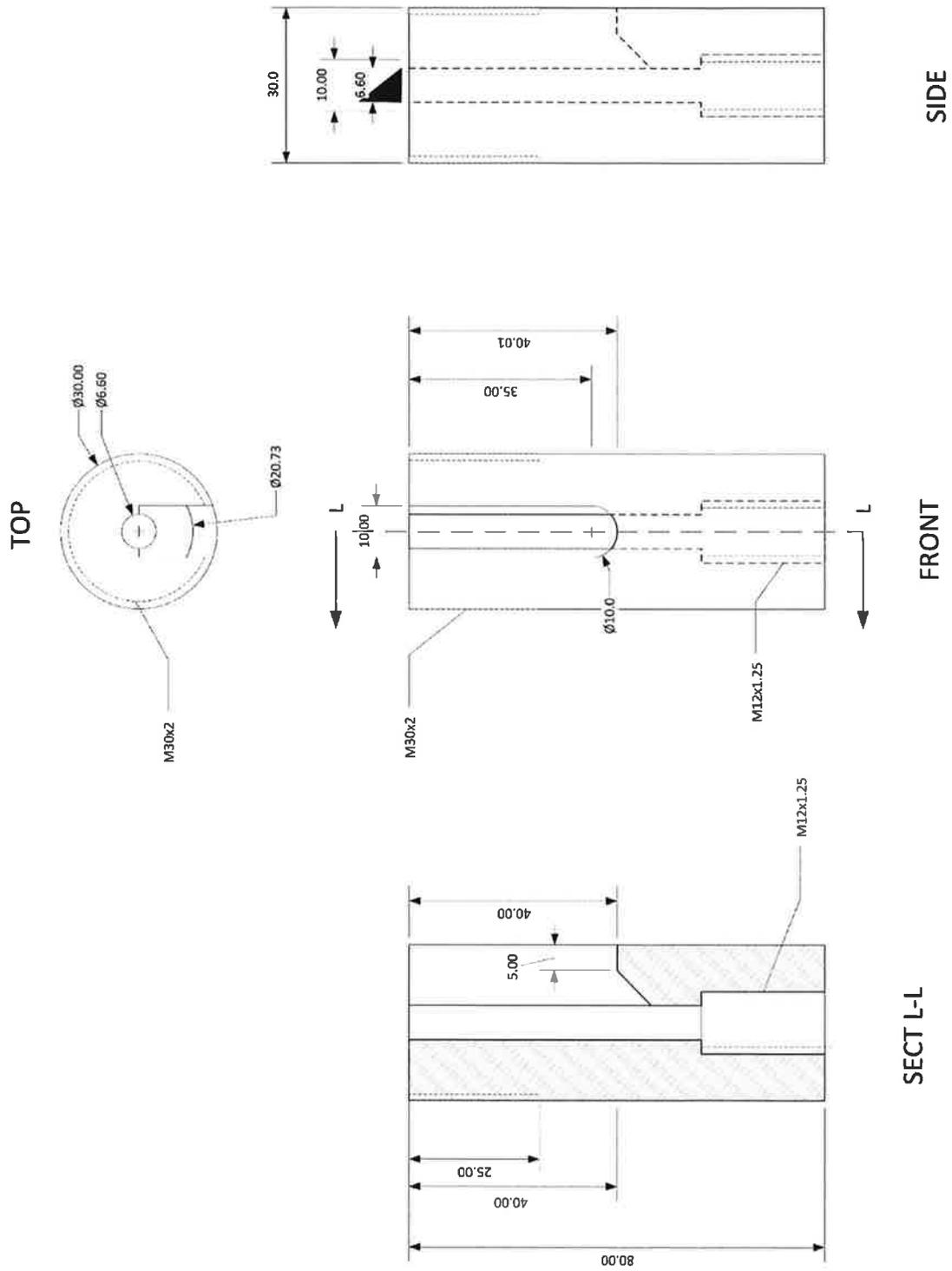
ITEM	QTY.	
Cap Top	1	
Cap Body	1	
SHAFT		SEE PAGE 11



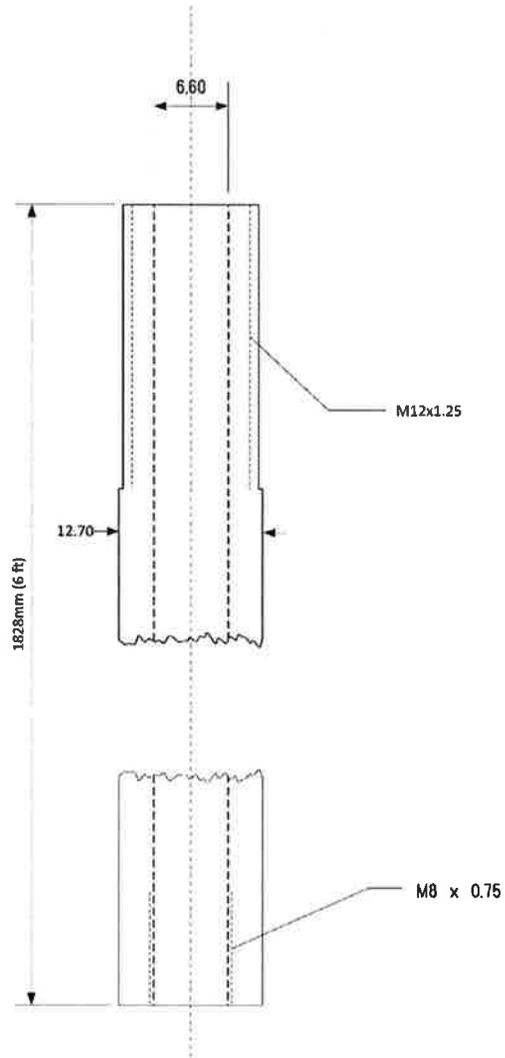
TITLE	DESCRIPTION		Texas A&M AgriLife Research 6500 Amarillo Blvd W Amarillo, TX, 79106	
CAP ASSEMBLY, ANNOTATED	FULLY ASSEMBLED PROBE CAP *NOTE: ONLY ITEMS IN PARTS LIST ARE REQUESTED			
DRAWN BY CHARLES HILLYER	MATERIAL 304 SS	ALL DIMENSIONS IN MILLIMETERS		
FILENAME ENDOSCOPE 18.VSDX	SCALE 1: 1	PAGE 5 OF 9	DRAWING NO. 2	DATE 2/12/2018



TITLE CAP TOP		DESCRIPTION		Texas A&M AgrLife Research 6500 Amarillo Blvd W Amarillo, TX, 79106
DRAWN BY CHARLES HILLYER		MATERIAL 304 SS	ALL DIMENSIONS IN MILLIMETERS	
FILENAME ENDOSCOPE 18,VSDX	SCALE 1: 1	PAGE 6 OF 9	DRAWING NO. 2	
		DATE 2/12/2018		

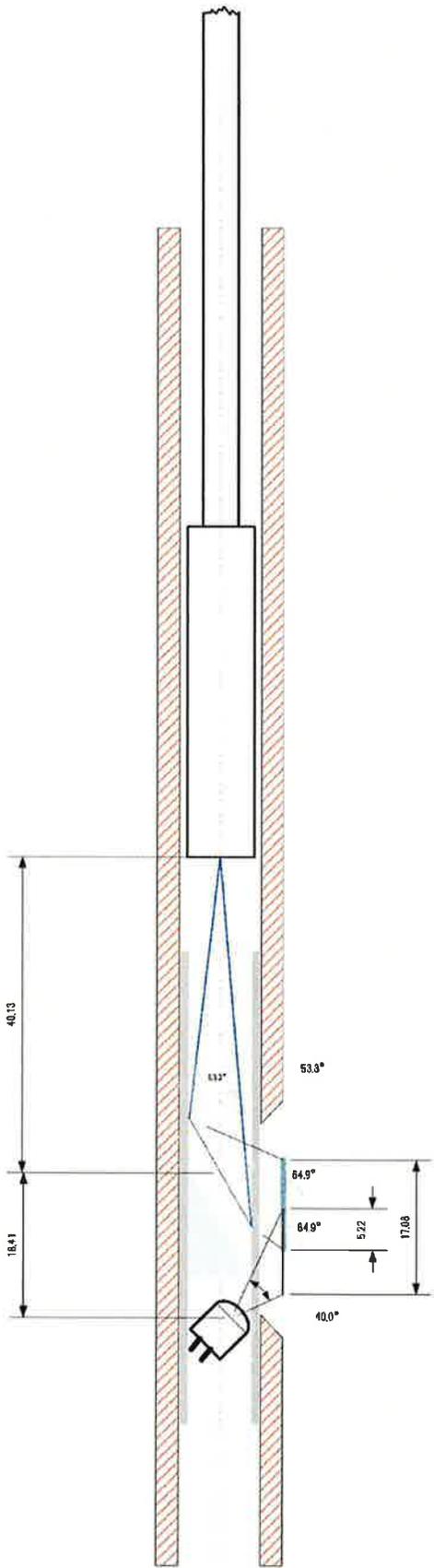


TITLE CAP BODY		DESCRIPTION			Texas A&M AgriLife Research 6500 Amarillo Blvd W Amarillo, TX, 79106
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FILENAME ENDOSCOPE 18.VSDX	SCALE 1: 1	PAGE 7 OF 9	DRAWING NO. 2	DATE 2/12/2018	



TITLE	SHAFT		DESCRIPTION		Texas A&M AgriLife Research 6500 Amarillo Blvd W Amarillo, TX, 79106
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CHARLES HILL YER		6500 Amarillo Blvd W Amarillo, TX 79106					
FILENAME		SCALE	PAGE	DRAWING NO.		DATE	
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Appendix B: Image Processing Code

The following code is used to filter the video images captured by the endoscope. The code is written in R (<https://www.r-project.org/>) and uses the ffmpeg (<https://www.ffmpeg.org/>) utility to extract individual frames from the video stream. General flow of the code is as follows:

1. Build a mask by estimating per-pixel variance across all frames
2. Use the mask to remove extraneous portions of the image
3. Estimate the probe displacement by comparing adjacent images
4. Composite all frames into a single image using the displacement estimates

```

library(ggplot2)
library(magrittr)
library(imager)
library(data.table)
library(stringr)
library(R.utils)
library(parallel)
library(pbapply)

proj.dir <- "C:/chillyer/projects/Soil Endoscope/caps"
caps.dir <- "out"

run.test <- function()
{
mask.name <- "tape1_mask3.png" base.name
<- "tape1_" cropped.base.name <-
"cropped_tape1_"

fns <- dir(file.path(proj.dir, caps.dir)
, pattern=cropped.base.name, full.names=TRUE ) fns <-
fns[770:870]

mask.img <- load.image( file.path(proj.dir, mask.name))

delta.tbl <- build.delta.tbl(fns, window.size=35, mask.img, cluster.count=6)

result.img <- composite.frames(delta.tbl, mask.img)

result.img.file.name <- paste0(base.name
, as.character( format(Sys.time(), "result_%Y-%m-%d_%H-%M-%S.png") ))

save.image(b, file.path(proj.dir, result.img.file.name))

}

#####
build.mask <- function(fns, save.table.as="maskTable.csv")
{
acc <- load.image(fns[1]) acc
<- grayscale(acc)
acc <- as.data.table(as.data.frame(acc))
acc[,mu:=0]
acc[,M:=0]
acc[,value:=NULL]
setkey(acc, x, y)

frame.index = 0

for(fn in fns)
{
frame.index <- frame.index + 1

printf("Frame: %d, fn:%s\n", frame.index, fn)
img <- as.data.table(as.data.frame(grayscale(load.image(fn))))
setkey(img, x, y)
acc[img, c("mu", "M"):=online.variance(mu, M, i.value, frame.index)]
}
acc[,M:= sqrt( M / (frame.index-1) ) ]

write.csv(acc, save.table.as)

acc[,mu:=NULL]

```

build-mask.r

```

setnames(acc, "M", "value") img
<- as.cimg(acc) return(img)
}

#####
online.variance <- function (mu, M, x, k) {
d1 <- x - mu
mu.2 <- mu + d1/k d2
<- x - mu.2
M.2 <- M + d1*d2
return( list("mu"=mu.2, "M"=M.2) )
}

# Acc[ M:= M/(n-1) ]
# acc[c, c("mu", "M") :=online.variance(mu, M, i.value, 3)]

#####
apply.mask <- function(mask.img, frames)
{
frame.index=0 mask
<- mask.img>0
bb <- bbox( mask.img > 0)

for(fn in frames)
{
frame.index <- frame.index + 1 parts
<- str_split(fn, "[/]" )
ln <- length(parts[[1]])
base.name <- parts[[1]][ln]
cropped.name <- paste0("cropped_", base.name)
n.fn <- paste0(str_sub(fn, 0, -(str_length(base.name)+1)), cropped.name) n.fn
<- paste0(str_sub( n.fn, 0, -4), "png")
printf("Frame: %d, in:%s out:%s\n", frame.index, base.name, n.fn)

img <- load.image(fn) img <-
img*mask
img <- crop.bbox(img, bb)
save.image( img, n.fn )
}

}

get.base.fn <- function(fn)
{
parts <- str_split(fn, "[/]" )
return( parts[[1]][length(parts[[1]])] )
}

#####
build.delta.tbl <- function(fns, window.size, mask.img, cluster.count=4)
{
#convert mask to logical
mask <- mask.img > 0

tmp.img <- load.image(fns[1]) d1
<- dim(tmp.img)
d2 <- dim(mask)
if(!(d1[1] == d2[1] && d1[2] == d2[2])) stop("mask image dimensions mismatch")

offsets <-      -(window.size-1):(window.size-1)
offsets.tbl <- expand.grid(dx=offsets, dy=offsets)

```

```

lhs <- fns[1:(length(fns)-1)] rhs
<- fns[2:length(fns)]
fns.tbl <- mapply(c, lhs, rhs, SIMPLIFY=FALSE)

cl <- makeCluster(cluster.count)
clusterExport(cl, c("mask", "offsets.tbl"), environment())
clusterEvalQ(cl, library(imager))

result = tryCatch(
{
tmp <- pblapply(cl=cl, X=fns.tbl, FUN=build.translation.vector)
},
warning = function(w) { print(paste(w)) },
error = function(e) { print(paste(e)) },
finally = { stopCluster(cl);
print("Cluster stopped")
})
cat("par apply done\n")

print(str(tmp))

tmp <- do.call("rbind", tmp)

delta.tbl <- cbind("lhs"=lhs, "rhs"=rhs, tmp)

#force column types
delta.tbl$lhs <- as.character(delta.tbl$lhs)
delta.tbl$rhs <- as.character(delta.tbl$rhs)
delta.tbl$dx <- as.integer(delta.tbl$dx)
delta.tbl$dy <- as.integer(delta.tbl$dy)
delta.tbl$msse <- as.numeric(delta.tbl$msse)
rownames(delta.tbl) <- NULL

write.csv(delta.tbl, "delta_table.csv", row.names=FALSE)
return(delta.tbl)

}

#####
build.translation.vector <- function(fn.lst)
{
a <- load.image(fn.lst[1]) * mask b
<- load.image(fn.lst[2]) * mask

f1 <- function(XX){ return( sqrt(mean( ((imshift(a, XX[1], XX[2])*mask) - (b*imshift
(mask, XX[1], XX[2])) )^2 )) ) }

tmp <- apply(offsets.tbl, 1, f1)
d <- offsets.tbl[ which.min(tmp), ]

d <- cbind(d, "msse"=tmp[which.min(tmp)])
names(d) <- c("dx", "dy", "msse")

return(d)
}

#####
composite.frames <- function(delta.tbl, mask)

```

```

{
pair.count = dim(delta.tbl)[1]

#estimate final image dimensions
dim.mask <- dim(mask)
w <- dim(mask)[1]
h <- dim(mask)[2]
cx <- cumsum(delta.tbl$dx) cy
<- cumsum(delta.tbl$dy) mx <-
max(abs(cx)) + 2*w my <-
max(abs(cy)) + 2*h

#make the base have same even/odd as the mask mx
<- ifelse(mx%%2 != w%%2, mx+1, mx)
my <- ifelse(my%%2 != h%%2, my+1, my)

mx2 <- mx/2 - w/2 +w%%2 my2
<- my/2 - h/2 +h%%2

printf("estimate image dime: mx2:%d my2:%d \n", mx2, my2)

#make a plot of the camera displacement and associated displacement estimate error
delta.tbl$cx <- cx
delta.tbl$cy <- cy
plt1 <- ggplot(delta.tbl, aes(x=cx,y=cy))
+ geom_line(aes(color=msse), size=2)
+ geom_point(aes(color=msse, size=msse))
plotFileNam <- as.character( format(Sys.time(), "displacement summary %Y-%m-%d_%H-%
M-%S.png") )
png(file=plotFileNam, width=10, height=10, units="in", res=200 )
print(plt1)
dev.off()

printf("setup: w:%d, h:%d, mx:%d, my:%d, mx2:%d, my2:%d, \n", w,
h, mx, my, mx2, my2)

base <- imfill(x=mx, y=my, val=c(0,0,0) )

#paste the first image in
printf("base: %d, %s \n", 0, delta.tbl[1,"lhs"]) nxt
<- load.image(delta.tbl[1,"lhs"]) %>%
resize(mx, my, interpolation_type=0) %>%
imshift( mx2, my2 ) base <-
base + nxt

#iterate over all the remaining images
for( frame.index in 1:pair.count)
{
sx <- mx2-cx[frame.index] sy <-
my2-cy[frame.index]

printf("Frame: i=%d, cx=%d, cy=%d, sx=%d, sy=%d, %s \n",
frame.index, cx[frame.index], cy[frame.index], sx, sy,
get.base.fn(delta.tbl[frame.index,"rhs"]))

nxt <- load.image(delta.tbl[frame.index,"rhs"]) %>%
resize(mx, my, interpolation_type=0) %>%
imshift( sx, sy )

l.msk <- base > 0 r.msk <-
nxt > 0 u.msk <- l.msk &
r.msk

```

```

base <- (
base * (l.msk & !r.msk)
+ average( imlist( base*u.msk, nxt*u.msk) )
+ nxt * (!l.msk & r.msk)
)

}
cat("composite.frames complete\n")
return(base)
}

#####
#####
get.sd.list <- function(fns )
{
frame.index <- 1
sd.tbl <- data.table( s=numeric(), cc=integer(), frame=integer() )

for(fn in fns)
{
a <-
as.data.table(as.data.frame(load.image(fn)))
a[,s:=sd(value),by=cc]
tmp <-
unique(a[,.(s,cc)])
tmp[, "frame" := frame.ind
ex]
sd.tbl <- rbindlist(list(sd.tbl, tmp))
printf("Frame: %d, in:%s \n", frame.index,
fn ) frame.index = frame.index + 1
}

return(sd.tbl)
}

#####
#####
#####
#####

```

