



Modeling a capacitive sensor with EStat

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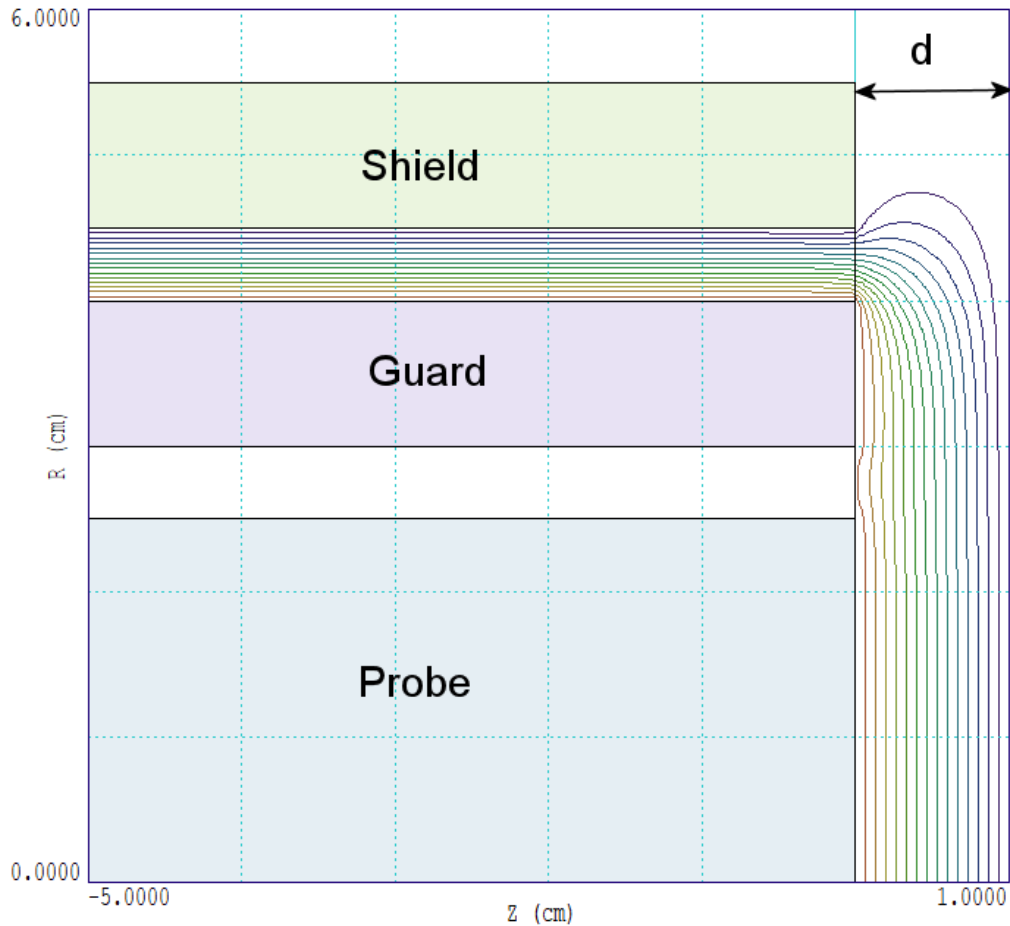


Figure 1: Capacitive sensor to determine height above a ground plane for $d = 1.0$ cm. The figure shows the assembly components and calculated equipotential lines. Dimensions in cm.

Determining the capacitance of a two-electrode system in **EStat** is easy. A solution is performed with one electrode set to 1.0 V and the other to 0.0 V. The *Volume integrals* command is applied with the solution loaded in the *Analysis* menu to find the global field energy U in joules. The system capacitance in farads is $C = 2U$. The procedure is more interesting with additional electrodes. To illustrate techniques, this report discusses the example of Fig. 1, a capacitive sensor to determine the height d above a ground plane. The cylindrical system consists of a central probe electrode of radius $r_p = 2.5$ cm, a guard electrode at the same potential and a grounded shield. The electrodes are separated by polyethylene insulators. In operation, an AC voltage is applied to the probe and guard electrodes. With a known variation of capacitance, the current drawn by the probe electrode gives the separation distance. The upper limit on d occurs when the capacitance between the probe and shield is comparable to or larger than the capacitance between the probe and the ground plane. The function of the guard electrode is to minimize probe-shield coupling.

The calculations had three goals:

- Determine the capacitance between the probe electrode and the ground plane as a function of the spacing d .
- Find the probe-shield capacitance and infer an upper limit on detectable spacing.
- Illustrate methods to carry out the calculations automatically using *Tasks* in **FPController**.

Runs were performed with eleven values of d between 0.25 and 20.0 cm. In all cases, the outer radial boundary was $r_{max} = 20.0$ cm. Because the fields were largely constrained to the gap, the results were not sensitive to the choice of the minimum axial boundary. It was set to $z_{min} = -5.0$ cm. The maximum axial boundary position was $z_{max} = d$. The shield electrode and the maximum axial and radial boundaries were set to ground potential. A potential of 1.0 V was assigned to the probe and guard electrodes.

The input file `CapacitiveSensorS.MIN` to define the geometry was prepared with the **Mesh** drawing editor and then modified with a text editor. The content is shown in Fig. 2. Notice that all instances of the parameter z_{max} were replaced with the symbol `%1`. If the **Mesh** program is called from a terminal window or batch file, the first pass parameter is substituted for the symbol. Therefore, if the current working directory contains the **Mesh** input file, then the terminal command to generate a mesh with gap spacing $d = 0.50$ cm is

```
C:\fieldp/tricomp/mesh.exe CapacitiveSensorS 0.50
```

There is one complicating factor. It would be inefficient to extend the final axial mesh resolution of 0.025 cm over regions $z > 2.0$ cm for larger values of d . An input file `CapacitiveSensorL.MIN` was prepared. It was identical to the previous one except for the following change in the axial mesh definition:

```
ZMESH
-5.000000  -2.000000  0.100000
-2.000000   2.000000  0.025000
 2.000000   %1        0.100000
END
```

In the calling batch file, runs with small values of d used `CapacitiveSensorS.MIN` and runs with larger values used `CapacitiveSensorL.MIN`.

```

1 * File: CapacitiveSensorS.MIN
2 * Short boundary
3 * MESH script (Field Precision)
4 *
5 -----
6 GLOBAL
7 ZMESH
8   -5.000000  -1.000000  0.100000
9   -1.000000  %1  0.025000
10
11 END
12 RMESH
13   0.000000  6.000000  0.050000
14   6.000000  10.000000  0.100000
15   10.000000  20.000000  0.200000
16 END
17 END
18 *
19 -----
20 REGION FILL AIR
21 L -5.000000  0.000000  %1  0.000000
22 L %1  0.000000  %1  20.000000
23 L %1  20.000000  -5.000000  20.000000
24 L -5.000000  20.000000  -5.000000  0.000000
25 END
26 *
27 -----
28 REGION FILL INSULATOR
29 L -5.000000  4.500000  0.000000  4.500000
30 L 0.000000  4.500000  0.000000  0.000000
31 L 0.000000  0.000000  -5.000000  0.000000
32 L -5.000000  0.000000  -5.000000  4.500000
33 END
34 *
35 -----
36 REGION FILL ELEC
37 L -5.000000  2.500000  0.000000  2.500000
38 L 0.000000  2.500000  0.000000  0.000000
39 L 0.000000  0.000000  -5.000000  0.000000
40 L -5.000000  0.000000  -5.000000  2.500000
41 END
42 *
43 -----
44 REGION FILL GUARDSLEEVE
45 L -5.000000  3.000000  0.000000  3.000000
46 L 0.000000  3.000000  0.000000  4.000000
47 L 0.000000  4.000000  -5.000000  4.000000
48 L -5.000000  4.000000  -5.000000  3.000000
49 END
50 *
51 -----
52 REGION FILL JACKET
53 L -5.000000  4.500000  0.000000  4.500000
54 L 0.000000  4.500000  0.000000  5.500000
55 L 0.000000  5.500000  -5.000000  5.500000
56 L -5.000000  5.500000  -5.000000  4.500000
57 END
58 *
59 -----
60 REGION GROUNDBOUND
61 L %1  0.000000  %1  20.000000
62 L %1  20.000000  -5.000000  20.000000
63 L -5.000000  20.000000  -5.000000  5.500000
64 END
65 *
66 -----
67 ENDFILE

```

Figure 2: Mesh input file CapacitiveSensorS.MIN

The **EStat** input file to control the electrostatic solution had the content

```
Mesh = CapacitiveSensor
Geometry = Cylin
DUnit = 1.0000E+02
ResTarget = 5.0000E-09
MaxCycle = 5000
* Region 1: AIR
Epsi(1) = 1.0000E+00
* Region 2: INSULATOR
Epsi(2) = 2.7000E+00
* Region 3: PROBE
Potential(3) = 1.0000E+00
* Region 4: GUARDS
Potential(4) = 1.0000E+00
* Region 5: SHIELD
Potential(5) = 0.0000E+00
* Region 6: GROUNDBOUND
Potential(6) = 0.0000E+00
EndFile
```

Solutions were analyzed with the analysis script:

```
* Region   Region
* number   name
* =====
*      1   AIR
*      2   INSULATOR
*      3   PROBE
*      4   GUARD
*      5   JACKET
*      6   GROUNDBOUND
INPUT CapacitiveSensor.EOU
OUTPUT CapacitiveSensor.DAT
SURFACEINT 3 -1
ENDFILE
```

The function of the **SURFACEINT** command depends on the current configuration file. For the default `estat_dielectric.cfg`, the command calculates and lists the surface integral of the magnitude of the normal electric field multiplied by ϵ_0 . The command in the script performed the integral over the surface of Region 3 (Probe) adjacent to Region 1 (air). For an applied potential of 1.0 V, the surface charge was equal to the capacitance in farads.

The control script `CapacitiveSensor.BAT` was prepared with the *Create task* command of **FPController** and then modified with a text editor. The function was to carry out the set of runs and to record the calculated values of probe capacitance in a text file `Abstract.txt`. The full set of calculations was performed by running the file using the *Run task* button in **FPController**. The file has the following content:

```
REM FP Controller batch file, Field Precision
IF EXIST Abstract.txt ERASE Abstract.txt

START /B /WAIT C:\fieldp/tricomp/mesh.exe CapacitiveSensorS 0.25
IF EXIST CapacitiveSensor.MOU ERASE CapacitiveSensor.MOU
REN "CapacitiveSensorS.MOU" "CapacitiveSensor.MOU"
START /B /WAIT C:\fieldp/tricomp/estat.exe CapacitiveSensor.EIN
START /B /WAIT C:\fieldp/tricomp/estat.exe CapacitiveSensor.SCR
findstr /l /c:"Normal integral:" CapacitiveSensor.DAT >> Abstract.txt

...

START /B /WAIT C:\fieldp/tricomp/mesh.exe CapacitiveSensorL 20.00
IF EXIST CapacitiveSensor.MOU ERASE CapacitiveSensor.MOU
REN "CapacitiveSensorL.MOU" "CapacitiveSensor.MOU"
START /B /WAIT C:\fieldp/tricomp/estat.exe CapacitiveSensor.EIN
START /B /WAIT C:\fieldp/tricomp/estat.exe CapacitiveSensor.SCR
findstr /l /c:"Normal integral:" CapacitiveSensor.DAT >> Abstract.txt

START /B /WAIT C:\fieldp\notify.exe
IF EXIST CapacitiveSensor.ACTIVE ERASE CapacitiveSensor.ACTIVE
```

The first command deleted any previous instance of `Abstract.txt`. Then there are eleven groups of six batch commands with different values of the pass parameter z_{max} . The commands in each group had the following functions:

- Call **Mesh** with different values of d . Use the input file `CapacitiveSensorS.MIN` when $d \leq 2.0$ and `CapacitiveSensorL.MIN` for larger values. The control parameters specify waiting until the process is complete before proceeding.
- Delete any previous instance of the standard **Mesh** output file `CapacitiveSensor.MOU`.
- Change the names `CapacitiveSensorS.MOU` or `CapacitiveSensorL.MOU` to the standard `CapacitiveSensor.MOU`.
- Perform the electrostatic solution.
- Run the **EStat** analysis script, making a listing file `CapacitiveSensor.DAT` with the result of the capacitance calculation.

- Open the file and add the line containing the capacitance calculation to the file `Abstract.txt`.

The final lines in the batch file made an audio signal when the run was complete and deleted a marker than indicated that the task was running. The calculation ran in the background and took only a few seconds. The end result was the file `Abstract.txt` with the content:

```
Normal integral: 7.011453E-12
Normal integral: 3.528376E-12
Normal integral: 1.775879E-12
Normal integral: 1.201070E-12
Normal integral: 9.293195E-13
Normal integral: 7.799638E-13
Normal integral: 5.524859E-13
Normal integral: 5.115425E-13
Normal integral: 4.989488E-13
Normal integral: 4.914112E-13
Normal integral: 4.895342E-13
```

Although most of the work building the batch file was performed with copy/paste operations in a text editor, the approach may seem like an overkill for the problem at hand. A motivation for this example was to provide a template and useful techniques for extensive calculations using any of our technical programs. Figure 3 plots the results. The dashed blue line is the approximation for parallel plate air capacitors with radius r_p much larger than d :

$$C = \frac{\epsilon_o(\pi r_p^2)}{d}. \quad (1)$$

The results were quite close for small values of d and the probe capacitance approached 4.7 pF at large d , the value for probe to shield coupling. The useful range of the device with the computed correction factors was about $d \leq 3.0$ cm.

A final topic is the relative merit of an alternate method for determining mutual capacitance, the energy method described in the tutorial *Calculating mutual capacitance with HiPhi* (www.fieldp.com/tutorials/mutualcapacitance.pdf). For each geometric configuration, the method involves more effort, requiring field energy comparisons for three solutions with different applied voltage combinations. In the current case, the capacitance values between the probe and guard and between the guard and shield were large compared to the capacitance between the probe and ground. The resulting energy sums involved small differences between large numbers, reducing the accuracy. For example, consider the case with $d = 0.25$ cm. With 1.0 V applied to the probe and 0.0 V to the guard, the total field energy was $U_{p0} = 35.9210$ pJ. The two other solutions gave $U_{0g} = 86.6481$ pJ and $U_{pg} = 58.9041$ pJ. Following the tutorial, the capacitance values are given by

$$C_{pg} = U_{p0} + U_{0g} - U_{pg}, \quad (2)$$

$$C_{p0} = U_{p0} - U_{0g} + U_{pg}, \quad (3)$$

$$C_{g0} = -U_{p0} + U_{0g} + U_{pg}. \quad (4)$$

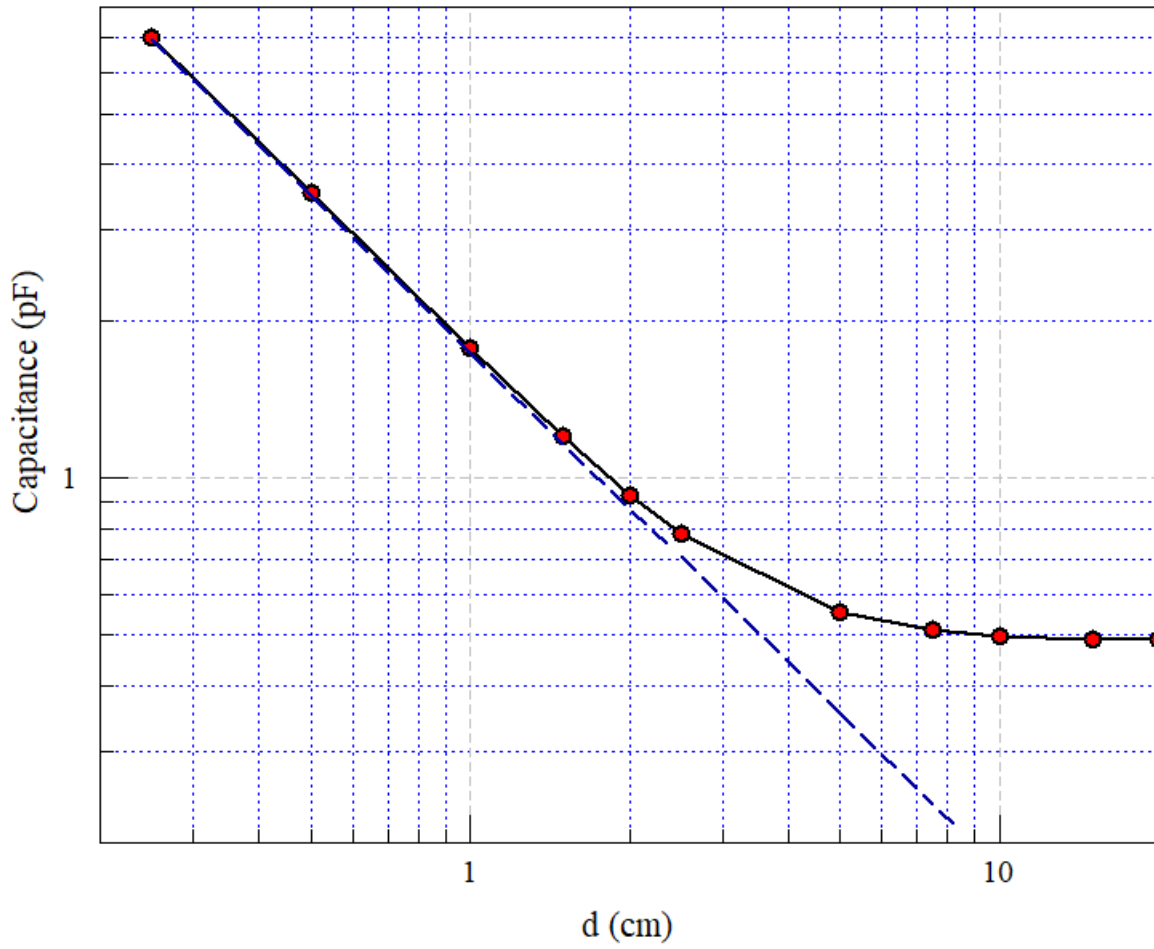


Figure 3: Capacitance as a function of the gap spacing d . The solid line is the prediction of Eq. 1.

Inserting values yields $C_{pg} = 63.66$ pF, $C_{p0} = 8.177$ pF and $C_{g0} = 109.36$ pF. The values for C_{pg} and C_{g0} are close to predictions for an ideal coaxial capacitor model (65.9 pF and 102.0 pF). The small value of C_{p0} is about 18% high. Values at larger gap spacings have larger errors. The implication is that surface integrals are preferable when feasible.

Input files for the calculations are available at:

https://www.fieldp.com/example_library/capacitive_sensor.html.