Electrical Capacitance Tomography system for determination of liquids in tanks rockets and satellites

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Abstract
One of the major problems in aerospace engineering is to determine the amount of fluid in the tank in a microgravity environment. There are several methods for determining liquid level in a tank; however, there are no proven methods to quickly gauge the amount of propellant in a tank while it is in low gravity. New and more accurate methods of measurement are being continually searched for. One of the interesting solutions is using Electrical Capacitance Tomography (ECT) for the determination of liquids in tanks rockets and satellites. The results which were carried out in gravity condition show that the method can directly measure the mass of fuel in the tank, as well as allow visualization of fuel distribution. This means that it is independent of position of the propellant inside the tank and independent of the propulsion system. This system is simple and completely non-invasive.

1. Introduction

The lack of gravity in the space environment makes it challenging to measure the amount of liquid propellant remaining in storage tanks. The main problem is the chaotic motion of fuel volume in the tanks due to no gravitational force. This chaotic motion causes a problems for the fuel system with diagnosing the accurate amount of fuel in the tank. There are several methods for determining liquid level in a tank while it is in low gravity. The most popular are: Pressure-Volume-Temperature Method (PVT Method) [1][2][3], Optical Mass Gauging (OMG) [4][5], Radio Frequency Mass Gauging (RFMG) [6].
The PVT application is set up for gauging the level of liquid in a propellant pressure tank via two methods. The first method is the ullage compression method (UCM). The level of liquid in the propellant tank is determined after adding a known delta volume of liquid to the tank without venting the ullage pressure. A real-time algorithm uses the known delta monomethylhydrazine (MMH) volume added, the delta temperature and the delta pressure of the tank ullage to calculate the volume of the tank ullage. The second method is called the external helium tank method (EHTM), and uses an external helium tank that is pressurized and connected to the propellant tank, but is initially isolated from the tank. Starting with stable pressures and temperatures in both tanks, the pressurized helium tank is opened to the propellant tank until the pressures and temperatures stabilize. The volume of the propellant tank ullage is calculated from the delta pressures and temperatures in the tanks. In these two methods, the level of the liquid is determined from the remaining volume in the propellant tank.

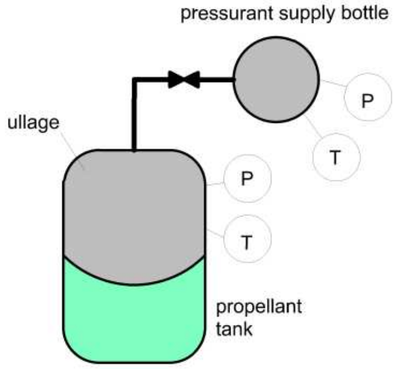


Figure 1: PVT gauging configuration [3].

The OMG is based on the premise that a propellant tank will act as a pseudo-integration optical sphere with respect to light source that is introduced into its interior. A spectrum of light which is emitted into an object can reflect from the surface, absorb and penetrate through the object. It is assumed that light, which is measured at a given tank port, will be proportional to the fraction of the input light that is not absorbed. In this case, this is related to the propellant mass or volume fraction. For any particular material, the transmission or absorption spectrum is unique.

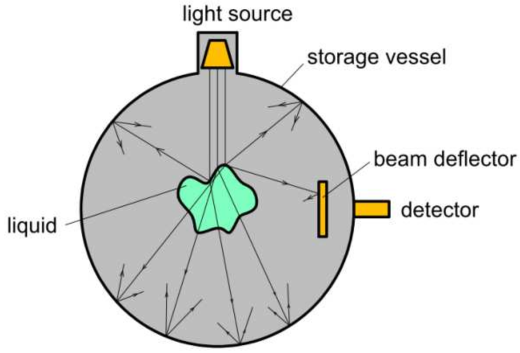


Figure 2: Optical Mass Gauging schematic [5].

The RFMG technique measures the electromagnetic eigenmodes or natural resonant frequencies of a tank containing a dielectric fluid. The hardware components consist of an antenna probe mounted internal to the tank and an RF network analyzer that measures the reflected power. At a resonant frequency, there is a drop in the reflected power, and these inverted peaks in the reflected power spectrum are identified as the tank eigenmode frequencies using a peak-detection software algorithm. This information is passed to a pattern-matching algorithm, which compares the measured eigenmode frequencies with a database of simulated eigenmode frequencies at various fill levels. A best match between the simulated and measured frequency values occurs at some fill level, which is then reported as the gauged fill level.

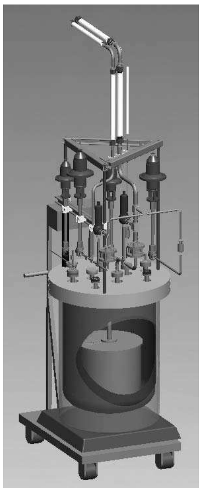


Figure 3: View of tank used for RFGM tests in liquid methane [6].

Each of methods have advantages and disadvantages, as well as varying feasibility for space flight applications. Many of these methods are not suitable for low gravity environments simply because they rely on gravitational forces to maintain a uniform distribution in the substance being gauged. In addition, some techniques capable of liquid or vapor mass gauging are not adequate for solid mass gauging due to their inability to discriminate between the presence of each form. To succeed in properly measuring the amount of fuel present in a tank that is exposed to a variable gravity environment, a technique must be reliable independent of fluctuations in gravitational forces, changes in mass distribution and changes in properties, which may be associated with changes of state or compressibility.

2. Electrical Capacitance Tomography system.

ECT is a measurement technique that reconstructs dielectric constant distribution in an object by measuring the capacitances between the electrode pairs, which are mounted around the object. A typical application is real time monitoring of multi-component flows within pipelines. Specific applications where ECT has been successfully

exploited include solid-gas and liquid-gas systems, such as fluidized beds, pneumatic conveying, multi-phase flow and combustion [7][8][9]. In principle, ECT is used to investigate and monitor any process where materials are non-conducting, and the other phases and components have differing values of permittivity.
A typical ECT system has three main units: a sensor, a measurement system and a computer.

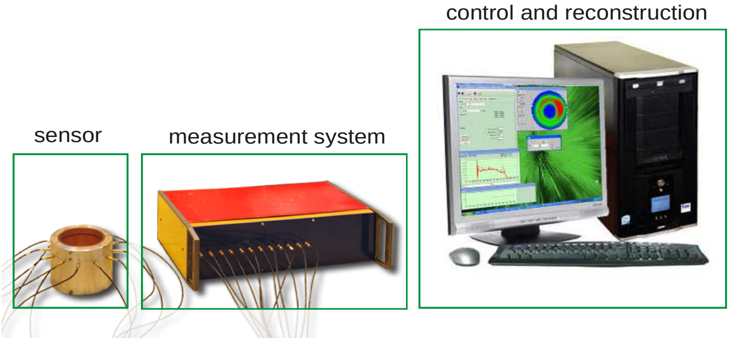


Figure 4: ECT system.

The sensor consists of a set of electrodes symmetrically mounted outside measurement space. The sensing electronics measure the capacitances for all possible electrode combinations, when the electrode sizes and location are fixed, depending only on the permittivity distribution inside the ECT sensor head. The computer system has two major functions. Firstly, it controls the measurement operations performed by the sensing electronics, and secondly, it uses the measurement data to reconstruct tomographic images.
At present, ECT is mainly used to visualization of permittivity distribution in two dimensions (2D). In 2D capacitance tomography, with its planar system of electrodes, some inhomogeneities and location of objects cannot be properly distinguished in three dimensional (3D) space. However, in the case of 3D capacitance tomography, the basic structure of the sensors and the measurement concept are the same as in 2D tomography. 3D imaging sensor contains much more electrodes, which arrangement enables to cover the whole research space. In this case, it is necessary to use multi-channel measurement systems. A popular solution used in ECT is to connect on principle: one electrode - one measuring channel. However, in this work, a new measurement system was designed and performed.

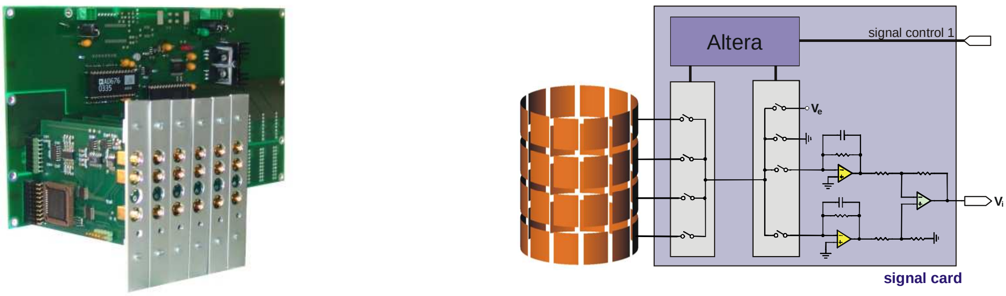


Figure 5: View of capacitance tomography electronic unit and the block diagram of signal card.

In our solution, one signal card can support up to four electrodes which lie in different planes, so the number of possible measurements slightly decreased. This results from the fact that the one signal card is not able to generate an excitation signal and to get measurements at the same time. In the case when all electrodes are connected to the separated signal cards, the number of possible measurements n is given by the following formula:

$$n = \frac{m \cdot (m-1)}{2} \tag{1}$$

where: m - total number of electrodes in sensor.

For the new solution the number of independent measurements n, is given by following formula:

$$n = \frac{w \cdot (w-1)}{2} \cdot r^2 \tag{2}$$

where: w – number of electrodes in one row;
r – number of rows in sensor.

The new solution reduced numbers of measurements, and so costs of constructing the new system were reduced. The present system has 16 signal cards, which allow measurement from 64 electrodes. For configuration, where every electrode is connected to the separate signal card, it was necessary to assemble 64 ones.
Due to the similarities mentioned above, 3D capacitance tomography can use the same reconstruction methods as 2D classic tomography. ECT images from capacitance measurements are generated using the Linear Back-Projection (LBP) algorithm. This algorithm is simple, fast and ideal for online reconstruction, but produces relatively low-accuracy images. For improving the accuracy of LBP images the iterative image computation methods are used. The most widely used iterative method to solve the problem in ECT is the Landweber technique, also called Iterative Linear Back Projection (ILBP). The full description of the algorithms can be found in many publications [10][11][12].
A very important step of the inverse process is to present reconstruction results and show them in a suitable and realistic form. 3D image presentation is always very demanding especially in view of calculation time and complex algorithms. Software has been written in Delphi® 2006 and OpenGL was used for visualization. OpenGL (Open Graphics Library) is a standard specification defining a cross-language cross-platform API for writing applications that produce 2D and 3D computer graphics. The interface consists of over 250 different function calls that can be used to draw complex three-dimensional scenes from simple primitives.

3. Spherical sensor

The sensor is one of the most important elements of the Electrical Capacitance Tomography. In principle, ECT is a non-invasive method, so the principle of the construction of the sensor is based on placing a set of electrodes around the measurement area, so that the flow or distribution medium inside the tank has not been disturbed.
The spherical tank is the most common satellite pressure vessel configuration. Thousands of spherical tanks have flown since the inception of the space age. Spherical geometry offers the best pressure performance, therefore, it provides the most mass-efficient pressure vessel design. In this work, a new 24-electrode capacitance sensor has been developed. The electrodes have been mounted on a non-conducting plastic sphere with 217.0 [mm] in diameter, which have been arranged in three planes where each planes consist of 8 electrodes. The total volume of sphere is Vsphere=5.34 [dm3]. The sensor includes radial and axial guard electrodes, which are used to reduce the external coupling between the electrodes and to achieve improved quality of measurements. Size of the electrodes was chosen so that the area of each is similar. Two holes were made in the lower and upper spheres. These holes allow for easy filling and emptying of the sphere.

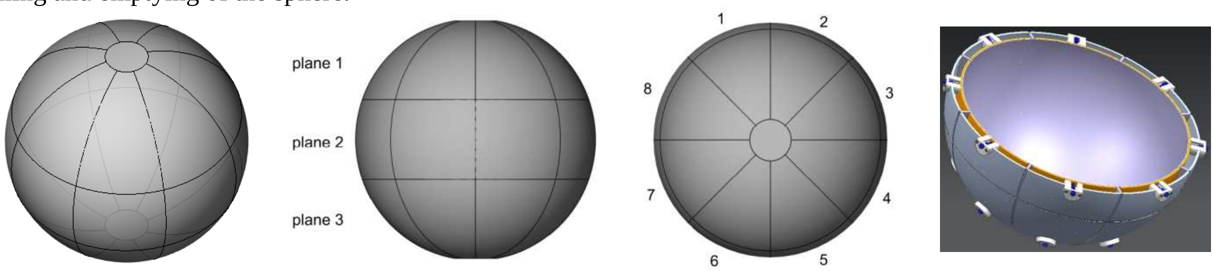


Figure 8: Visualization of 3D sensor geometry.

Figure 9: View of spherical capacitance sensor.

The main problem in 3D modeling and reconstruction is the mesh size. Meshes in 2D tomography usually have a few hundred nodes. In the case of 3D tomography the number of nodes reaches up to thousands, so has a serious impact on the reconstruction speed in online mode. The finite-element method (FEM) technique (software: Ansys® Inc.) was applied to obtain the distribution of an electric field within the sensor volume. The sensitivity map of electrode pair i-j at a spatial location [x,y,z] can be calculated by vector multiplication of two electric fields, which are normal to the potential distributions. In the reconstruction a sensor which consists of 9705 nodes where the total number of elements is 52487 was used.

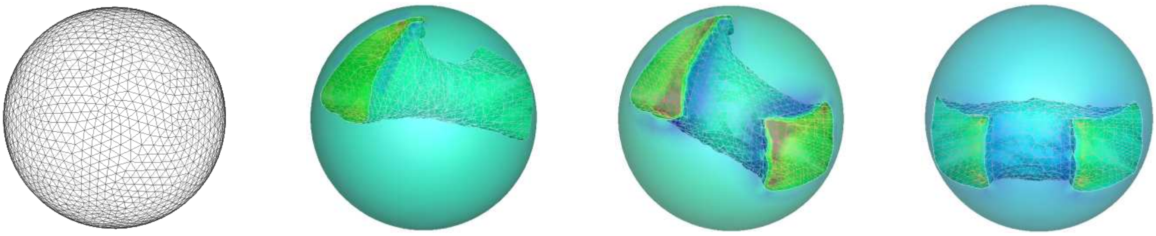


Figure 10: View of mesh and potential distribution in the 3D ECT sensor

4. Research

The most common propulsion systems are liquid, which is a combination of a chemical fuel with an oxidizer. A popular solution is to use monomethylhydrazine (MMH) as the fuel, and nitrogen textroxide (NTO/MON-3) as the oxidizer. For safety in our research quartz sand was used to fill the sensor.

Three methods were used to determine the content of the sphere. The first method uses the calculated values of normalized dielectric permittivity, obtained using the LBP algorithm (V_{LBP}). The second method uses a normalized value of dielectric permittivity obtained using the algorithm ILBP (V_{ILBP}). The last method is based on normalized values capacitance between electrodes (V_c).

$$V_{LBP} = \frac{\sum_{i}^{n_w} k_{i(LBP)}}{n_w} \cdot V_{sphere} \tag{3}$$

$$V_{ILBP} = \frac{\sum_{i}^{n_w} k_{i(ILBP)}}{n_w} \cdot V_{sphere} \tag{4}$$

$$V_C = \frac{\sum_{i}^{n} C_{i(k)}}{n} \cdot V_{sphere} \tag{5}$$

where:

$k_{i(LBP)}$ - the normalized pixel permittivities obtained using the algorithm LBP
$k_{i(ILBP)}$ - the normalized pixel permittivities obtained using the algorithm ILBP
$C_{i(k)}$ - the normalized capacitances for k electrode-pair
n_w - the number of nodes representing the sensor
n - the number of unique electrode pair combinations
V_{sphere} - total volume of a sphere

Research was divided into two stages. The first stage of research was carried out to determine how much fluid has been added when the tank stayed at rest. After entering a precisely defined dose of sand into the tank, a measurement system based on recorded data again determined the contents of the tank. LBP algorithm and IBLP algorithm with 100 iterations were used in reconstruction.

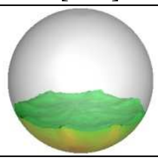
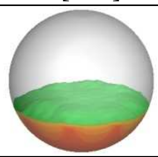
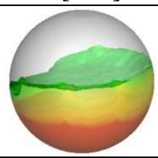
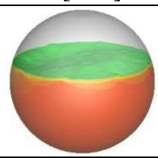
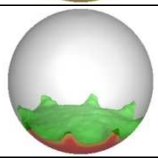
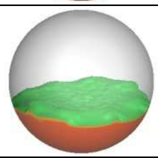
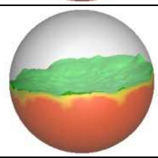
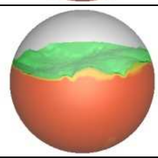
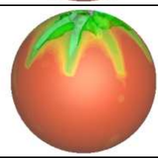
	1 [dm^3]	2 [dm^3]	3 [dm^3]	4 [dm^3]	5 [dm^3]
LBP					
ILBP					

Figure 11: Reconstructed images for different contents of the tank

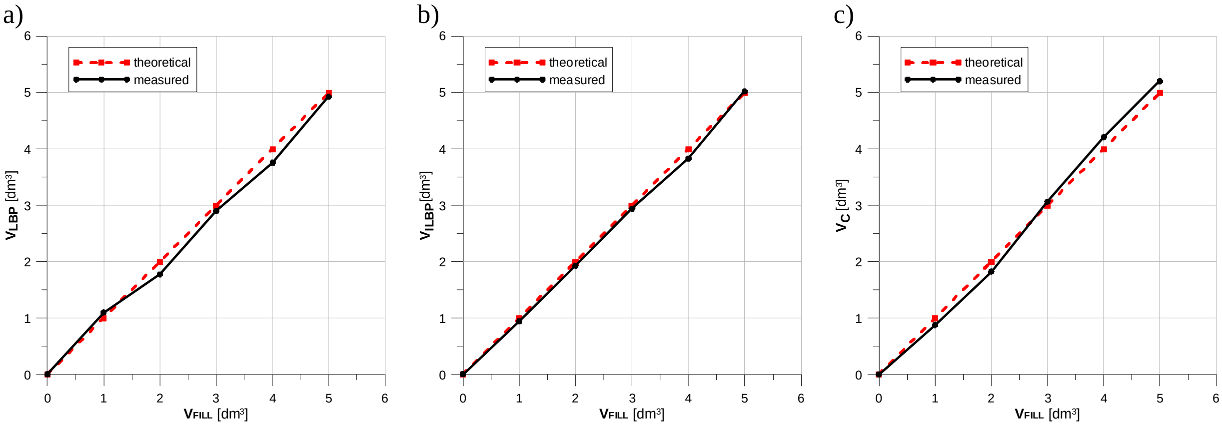


Figure 12: Variation of tank contents for different methods.

In addition to the reconstructed images, in order to evaluate performance of each method, relative error was determined. The norms of the original (V_{FILL}) and obtained V_{LBP}, V_{ILBP}, V_C volume can be used to calculate the relative error:

$$e_{LBP,ILBP,C} = \left\| \frac{V_{FILL} - V_{LBP,ILBP,C}}{V_{FILL}} \right\| \cdot 100 \quad [\%] \tag{6}$$

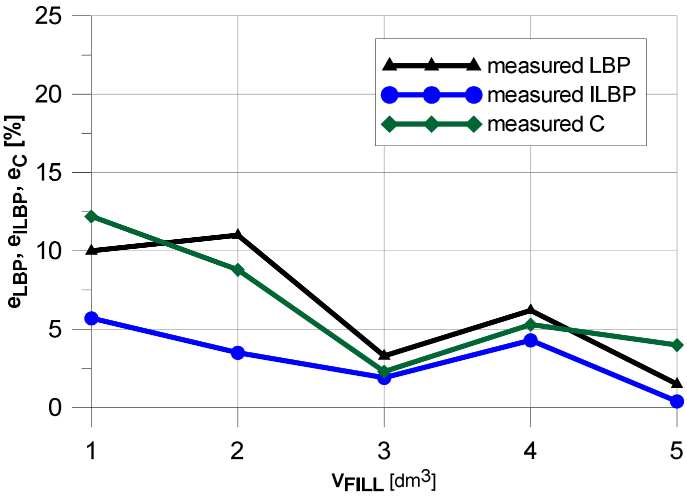


Figure 13: The relative error for different measurement method and tank contents.

The next phase of the study was to determine the level in the tank for different sensor positions. In this way, a different position of the tank was simulated depending on the position of the satellite in space. Due to the fact that the shape of the electrodes is irregular, changing the position of the tank will ebable to estimate the impact of distribution of the material inside the tank to the accuracy of the reconstruction and fuel content. The reconstruction was made for four tank contents 1, 2, 3, 4 [dm3] and for a few tank positions. In the analysis of the results the previous equation was used.

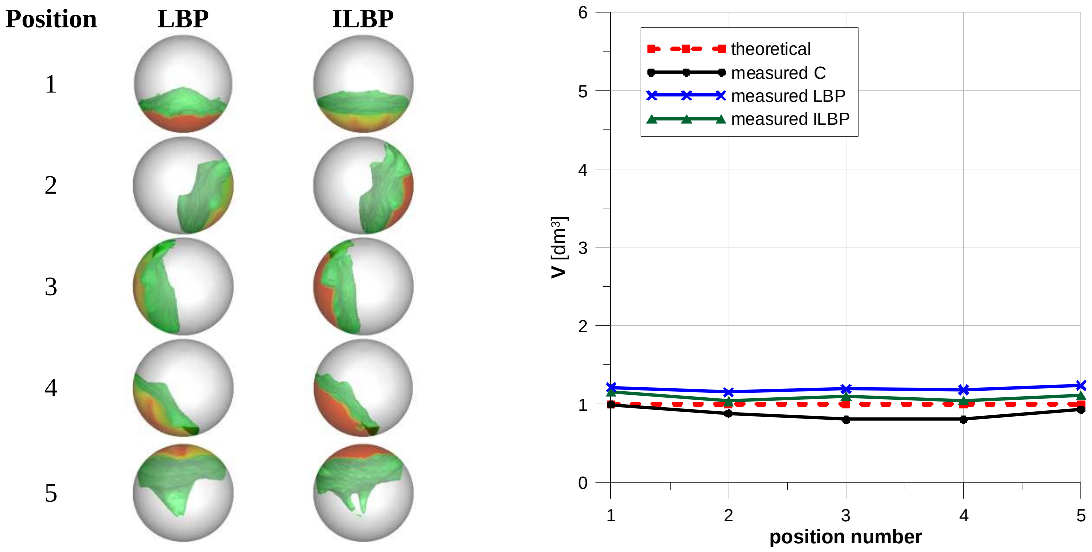


Figure 14: Reconstructed images for 1 [dm^3] tank contents

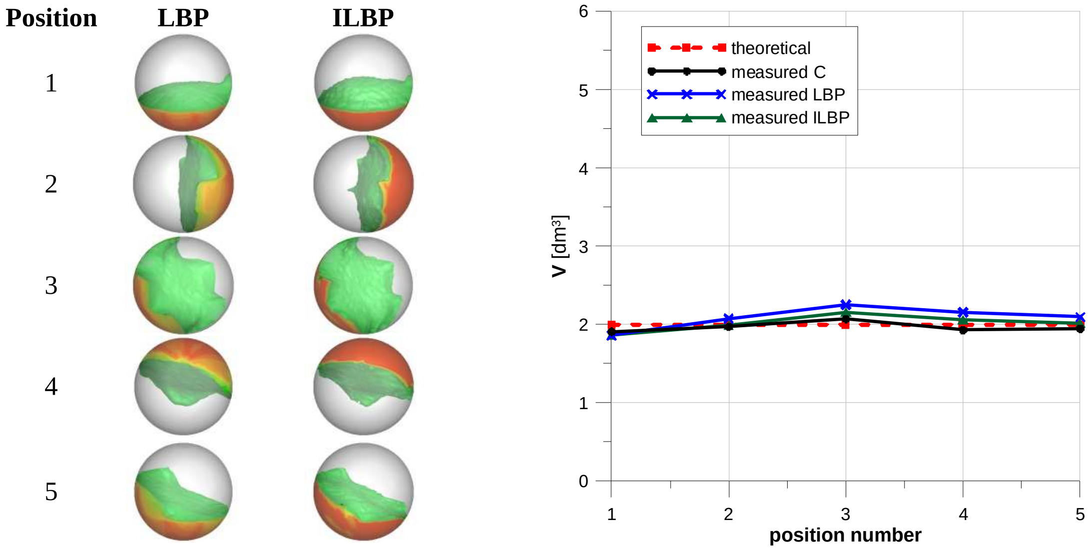


Figure 15: Reconstructed images for 2 [dm^3] tank contents

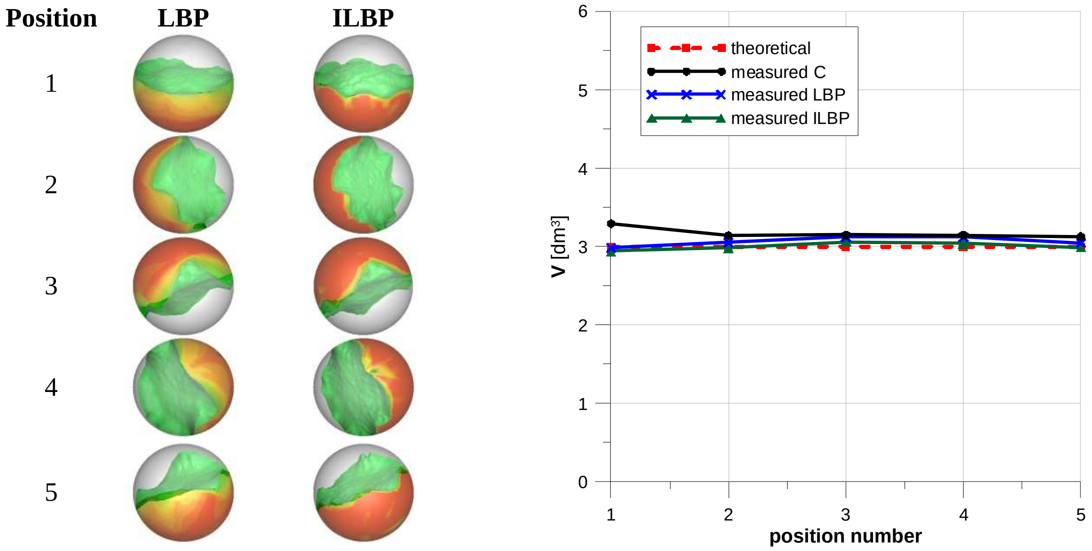


Figure 16: Reconstructed images for 3 [dm^3] tank contents

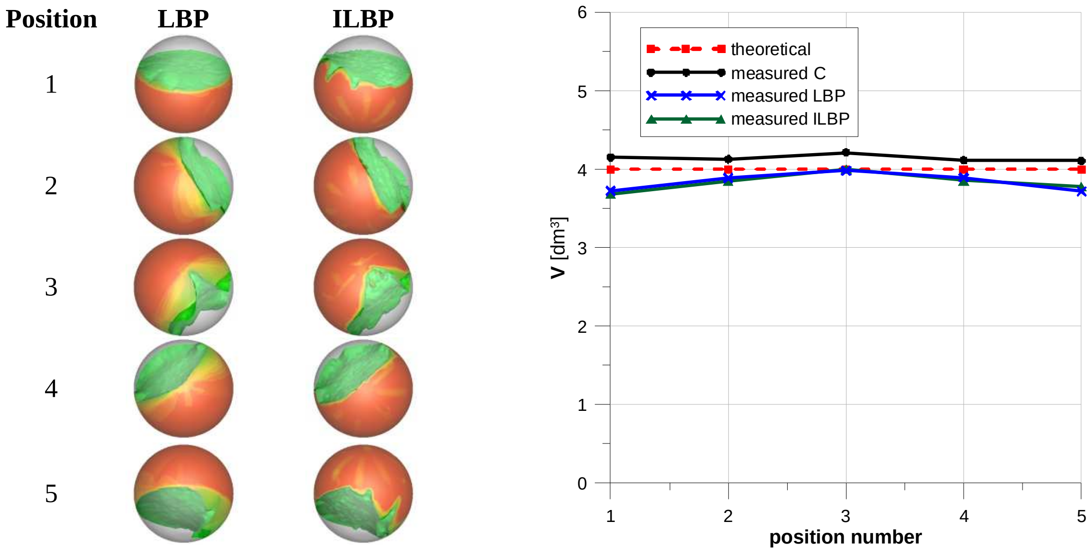


Figure 17: Reconstructed images for 4 [dm^3] tank contents

Additionally, in the case of the reconstructed images, , the average value of relative error from five tank contents was determined in order to evaluate performance of each method.

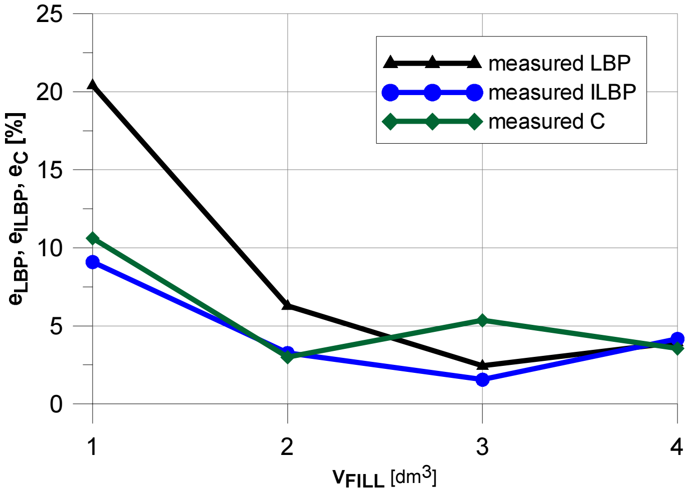


Figure 18: The relative error (rotate tank) for different measurement methods and tank contents.

4. Conclusions

Satellites fuel systems working in a space environment encounter difficulties directly connected with anti-gravitational conditions during their operations on the orbit. The main problem is the chaotic motion of fuel volume in the tanks due to no gravitational force. This chaotic motion causes problems for fuel system in diagnosing the accurate amount of remaining fuel in the tank.

In this work, results show that the ECT system is an interesting solution that may be used in monitoring systems of fuel tanks of satellites. We can see that the relative error is less than 10% when the content of the sphere was determined with the help of normalized values of dielectric permittivity obtained using the ILBP algorithm. Measurement data collected allowed not only to reconstruct the changes taking place inside the tank, but also allowed us to determine the contents of the tank. In future work, an improved ECT system will be developed to improve the resolution, and to present the images of the contents tank in real time. The proposed technique will be tested in low gravity environments by using a microgravity lift. It is believed that the ECT system holds significant promise for the future of detecting distribution and determining the amount of fluid in tanks rockets and satellites.

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