Miniaturized robotics:
The smallest camera operator bot pays tribute to David Bowie.

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***Abstract*— Robotics and 3D printing pave the way of new methodologies for the future of many industries, but can also be used for original artistic projects including technological challenges. Imagine a film studio smaller than the size of your finger, an actor whose height is smaller than the thickness of your fingernail, and a camera using electrons instead of photons: these are the filming ingredients of the innovative film "Stardust Odyssey". Several years of development have been necessary to propose high precision miniaturized robots able to position 3D printed microfigurines in a Scanning Electronic Microscope (SEM) to produce the film released on November 27th, 2019. This original film is available online on [1]. The film paying tribute to David Bowie has set a Guinness Book World record: the smallest 3D stop-motion animation character in the world [3].**

I. Introduction

The purpose of Stardust Odyssey as a film project was to illustrate, in an original way, the capabilities of robotics & 3D printing at microscale. Our goal was to create a stop-motion film [2] with 3D figurines with a maximum 300µm height (see figure 1). It requires the design and the production of the microfigurines and also to position them with a micrometric precision in front of an imager. The microfigurines were printed with a 2-photons 3D printer available in Université Libre de Bruxelles, whose resolution is about 1 micron. At this scale, the best way to visualize three-dimensional objects is the Scanning Electronic Microscope (SEM) operating in a vacuum chamber. The microfigurines were metallized to be visible in the SEM. In order to position figurines in front of the imager, high precision miniaturized robots working in vacuum and developed in FEMTO-ST Institute have been used.

Two other stop-motion films in micro-nanoscale have been produced in recent years. Both films consist in two categories of the Guinness book world record [3, 4]. The film "A Boy and His Atom" produced by IBM company, was performed in a scanning tunneling microscope enabling to visualize single atoms on a substrate [5]. This one-minute black & white film shows a boy playing with a ball, which is a mono-oxyde molecule. The character in this film is significantly smaller (few nanometers in height) than in the Stardust Odyssey film (300µm) but the character is a planar drawing and not a real 3D figurine.

The second world record deals with the smallest 3D figurine in a stop-motion animation. The record was initially established for the "Dot" film produced by Nokia company [6]. In this 2-minute film shot with a Nokia N8 phone, a tiny (9 mm) 3D figurine of a girl discovers the magical millimeter scale world, flying on a bee. The 80-second film presented in this article is the new holder of this second Guinness world record [3]. Indeed, the Stardust Odyssey figurine is 30 times smaller than the previous world record [6]. However, Stardust Odyssey is a black&white film when the previous record holder ("Dot" film) was a color film.

Each key technology has required ad-hoc developments to build the film. The multidisciplinary technological challenges and the methodologies are described in the sections below. In other words, the costume designer, the makeup artist, the robotic cameraman, and the film maker are presented in the article.

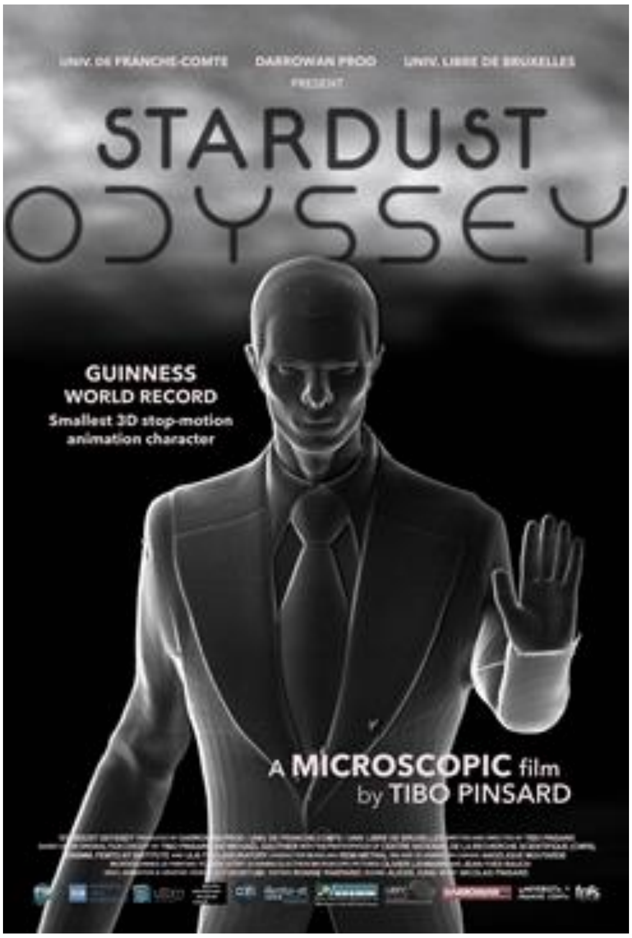

Figure 1. The stardust ODYSSEY official poster.

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II. The Costume designer: a 2 photons 3D printer

A. Challenges and objectives

This project requires a production technique compliant with the most important requirements: the size of the figurine and the figurine details, the 3D geometrical complexity, and the compatibility with the imaging process (ie the scanning electron microscope).

First, the figurines height is about 300 micrometers, and even smaller details must be included to provide some feeling of emotions, conveyed through the eyes, the face or the fingers of our micro-hero. Second, the microfigurines are not only small – only three times taller than the diameter of a human hair -, they include a high three-dimensional geometrical complexity, to reproduce the human aspect of the character. Third, the microfigurines must be produced in a conductive material, to avoid saturation by electron accumulation on insulative materials during the imaging process (see later on the section on the scanning electron microscope).

Focused ion beams systems could be used to sculp metallic materials at the required scale, but would not be suitable with the geometrical overhangs. Alternatively, we opted for the 2 photons lithography technique, a kind of 3D printer polymerizing submicron voxels of polymer resin with a laser [7]. The resolution and the geometrical versatility of the digital printing process make this technique the reference technique to print complex geometrical parts at the micron scale. The third criterion (conductive material) was circumvented by postprocessing the figurine with a metallic coating.

The optimization of all printing parameters was really challenging, allowing the researchers to push forward the frontiers of their equipment.

B. Basic principle of the printer and ad-hoc developments for the film

As aforementioned, 3D printing by 2 photons lithography enables the production of complex three-dimensional structures with submillimetric dimensions and submicronic details. The objects obtained allow researchers to explore phenomena at the microscopic scale in multiple fields: surface texturing, replication of bio-inspired structures, micro-robotics, molecular biology, pharmaceutical production, etc. At the Université libre de Bruxelles (ULB, Brussels), the researchers of the TIPs team study microfluidic phenomena, it means the properties of liquids at these very small scale.

When printing with two photons polymerisation, a microscopic lens is dipped into a liquid drop of photosensible resin that is deposited on a quartz substrate. The distance between the lens and the substrate is a bit above 300 µm which is the size of the figurines. Therefore, one of the main challenges when printing was to prevent any damage to the figurine due to the contact with the lens or the movement of the liquid resin induced by the lens (see figure 2). Moreover, as the printing is realized Z-layer by Z-layer, when the printing is too slow, the different layers of the figurine that are cantilevered (such as the arm, leg) will not stick together because of small residual movement in the liquid photoresist.

Once the printing is complete, the other main challenge appeared being the removal of the uncured resin that remains around the figurine without damaging it. To do so, the figurines were first sank into a developer solvent and then into Isopropanol. However, the regular cleaning process deformed the figurines cantilever part and sometimes completely detached the figurines from the substrate. Therefore, a smooth cleaning process was used where the figurines remained immersed during the whole cleaning process and the developer was gently replaced by isopropanol. However, even with this gentle development process, some figurines were still detached from the substrate. Therefore, for each figurine, the adhesion surface between the shoe and the substrate was analyzed and for some of them, it was mandatory to remove part of the sole or the heel to increase the adhesion surface to avoid adding a holding beam.

250 figurines have been printed to build the film on more than 20 different quartz holders. One example is proposed on figure 3.

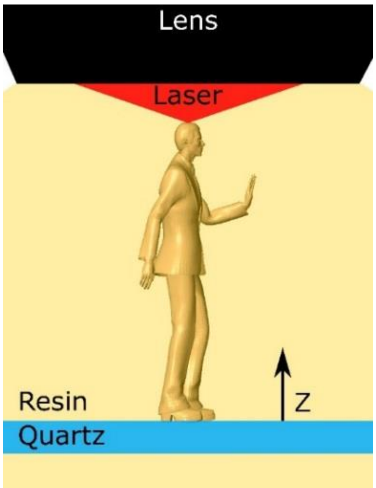

Figure 2. Schematic representation of the printing process

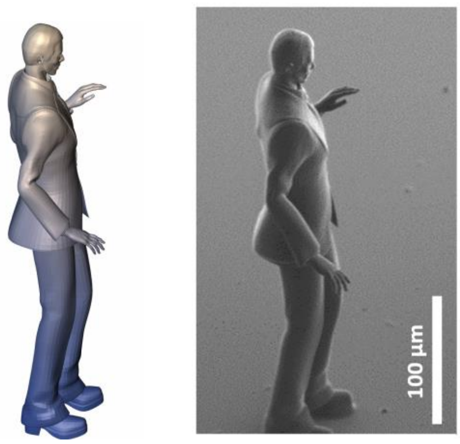

Figure 3. Example of a printed figurine (right) compared with the CAD model (left).

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III. THE MAKEUP ARTIST: A SPUTTERING MACHINE

After the 3D printing step, the figurines appear in transparent photoresist deposited on glass slides. This resin has two major drawbacks for film making in the electron microscope. The photoresist is insulating and transparent and it is impossible to produce optical and SEM images. It is therefore necessary to coat the figurines with a very thin layer of metal, thin enough so that the metal in the vapor phase does not deform the details of the figurines and thick enough to remove electronic charges during the vacuum electron imaging phases and in the electron microscope.

In this film, the tiny stop-motion animated David Bowie wears chromium clothes, since the metal deposited for dressing the figurines is chromium.

The process used to coat the chrome figurines is called PVD, Physical Vapor Deposition, and it takes place under vacuum. All the figurines are therefore first vacuum-packed in order to receive a thin layer of chromium in the range of 40 to 60 nanometers. This thin layer will allow to keep all the details of the 3D printing while offering a total coverage to achieve the evacuation of electronic charges during the imaging phases under an electron microscope. The chromium spraying process has been developed at high argon pressure to avoid direct chromium vapor spraying on resin printed figurines that do not withstand temperatures above 80°C. For a deposited thickness of 100 nanometers, we begin to observe melting phenomena on the surface of the figurines, especially on the face. For a deposited thickness of less than 30 nm, it is the charging phenomenon during electronic imaging that prevents the production of good quality images (see figure 4). We have therefore optimized the thickness deposited between 40 and 60 nanometers to achieve the film's objectives.

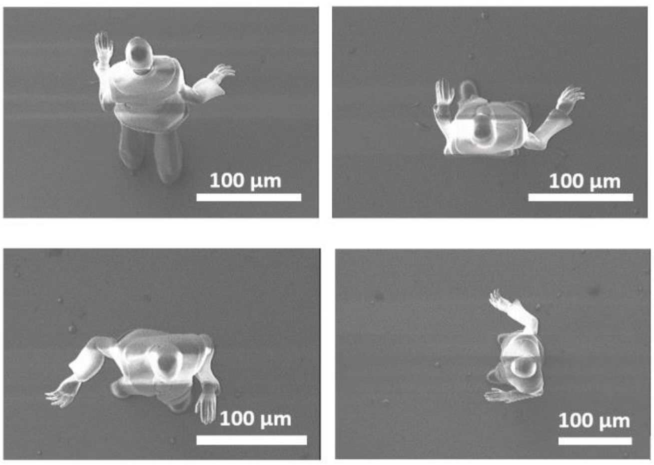

Figure 4. top view of figurines with different charge line effects due to electrons and conductivity of the materials during the imaging process. Small deformation of the arm.

IV. THE ROBOTIC CAMERA OPERATOR: A MICROROBOT IN A SCANNING ELECTRONIC MICROSCOPE

On a film set, the camera is usually moving around the actors. In Stardust Odyssey, the camera is static and all the film set and figurines are moving around it. Moreover, the required precision of the relative positioning of the figurine in the framework of the camera is significantly higher than in a conventional film. The last challenge comes from the size of the imager which is huge compared to the figurine. Indeed, the bottom of the SEM detector is a circle of 500 micrometers (see figure 4) larger than the height of the figurine (300 µm).

In Stardust Odyssey, two precision microrobots are necessary in order to place each figurine in the right position, front, side, back to make the pictures needed for each shot of the film. We also used a SmarAct Gmbh robot for introducing the star in the scene.

A. *Basic principle of the SEM microrobotic platform*

The pictures of the film have been made on an ad-hoc scientific equipment of FEMTO-ST institute named µRobotex platform [8]. This innovative powerful micro and nanofactory, is based on an Auriga 60 microscope produced by Zeiss. This microscope has a large vacuum chamber of 60x60x60cm3. On the top of the chamber, a SEM FEG column is installed with two detectors for retro diffused electrons and one detector for secondary electrons. The Focused Ion Beam -FIB- column, produced by Orsay-Physics, is positioned at an angle of 54° from the z-axis of the SEM column (see figure 5). Some pictures of the movie are realized with the FIB column. We can also use the Gas Injection System (GIS by Oxford Instrument) with three gases: Xenon Fluor, naphthalene and cyclopentadienyl-platinum for vapor deposition processes respectively carbon and platinum by Ion Beam Assisted Deposition (IBAD). This GIS enables to do nanocuting and nanoprinting and was not used for the movie pictures.

B. *Robotic under vacuum*

The robotic system is built with six individual stick-slip actuators from SmarAct Gmbh. The robotic structure is home assembled and all the robotic arms are controlled in order to obtain a very high accuracy on the object position. The moving steps are controlled with a Human / Machine / Interface (HMI) and the softwares are home made in order to combine high accuracy of positioning and synchronization of all axes in the assembly processes (see Figure 5). The control of the robotic system is based on the Kinematic Model (KM) to calculate the position of the object of interest in function of the value of the position of each actuation stages. The Kinematic Model is also used to build a CAD representation of the scene in order to provide to the Human operator a visual feedback on the robot configuration. Indeed, the robots are working in a vacuum chamber and are thus not visible from outside. The robot structures are characterized by the possibility of decoupling the Kinematic Model in a complete geometric model calibrated in order to obtain information about the position of the scene. Concretely, it is possible to control the robot in three different frameworks: the SEM framework, the FIB framework and the framework of each axis of the robot.

All the actuation stages are synchronized every 500 ms in position and in acceleration in order to control the system with a high accuracy. Using the magnification used in the film, the accuracy is around 10 nanometers in position. The high accuracy robot enables to position each figurine at their reference position to obtain each picture defined in the film scenario.

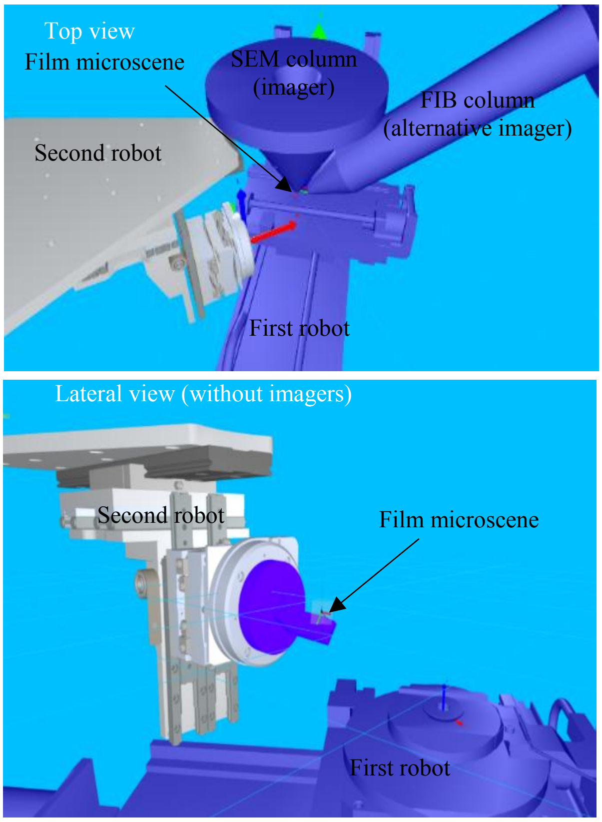

Figure 5. CAD model of the microrobots placed in the scanning electronic microscope. Top view: the SEM and FIB columns are used to provide the images. Side view: Both precision microrobots are used to position the film set in front of the imagers.

Figure 6. Control software of the robot developed for the film.

C. *Ad-hoc developments for the Film*

To make the different shots of the film, we have developed a specific software allowing to correctly position the figurine according to the previous images (see Figure 6). This software uses reference points to reposition the robot (and therefore the figurine) in a consistent way and enables a complete preview of the shots in real time or in "onion skinning" mode (see Figure 7) [2]. This way, we can make the hundreds of images of the film faster and more efficiently.

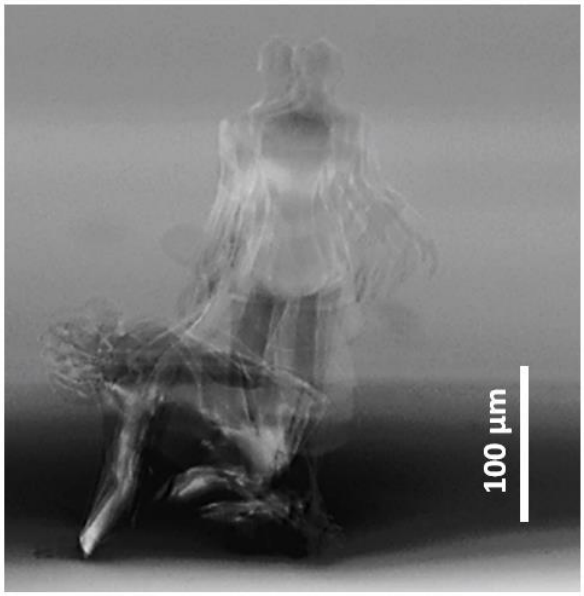

Figure 7. Method to reposition the picture relatively to the previous pictures: the onion skinning method.

V. A MACROSCOPIC FILMMAKER

Tibo Pinsard is a multi-award winning film director, working on fictions (series and shorts) and documentaries. He has directed for instance the short film Gorilla (121 film festival selections and 46 awards throughout the world). He recently directed a documentary on the Academy-award nominated production designer Anne Seibel, with Ralph Fiennes, director of photography Darius Khondji and Academy-award winner Rick Carter. Stardust Odyssey is Tibo's first animation film [9].

Tibo Pinsard's task on the production of Stardust Odyssey was to take care of all the artistic aspects (from framing to story, music, sound design…), as would happen on a « regular » shoot. But this time his partners were not a cinematographer, actors or a production designer, but scientists.

A. *Impact of the technology on the scenario*

Showing to an audience a world that has never been shown before in an animation film is part of Tibo's motivation. The director was fully aware that in order to make this specific short animation film, movie making techniques needed to be reimagined. Different meetings were necessary to figure out what was possible or not, filmmaking-wise: camera moves, camera angles, etc. Each technological constraint had to be addressed before defining the film scenario.

Prior to the stop-motion, Tibo Pinsard made the whole film in CGI (Computer Generated Imagery). It was used as a precious framework. The director first wrote a story (following the meetings with the scientists) and then drew a storyboard. At the same time, Rémi Létral created the CG model of the character. The face was built after a mugshot of David Bowie from the 1970s (see figure 8). Then Angélique Moutarde created a rig (a digital skeleton) for the character, in order to animate it. Based of Tibo Pinsard's storyboard, she did a first rough animation, that was then adjusted to match the director's wishes.

Once the CGI version of Stardust Odyssey was finished, Tibo Pinsard chose hundreds of key frames of the character's animation, that would then be transcoded into .STL files for the 3D printing stage. Then the film entered in the "shooting stage" of the microfigurines with the SEM. Each picture was framed respecting the director's vision.

Concretely, the film contains 12 pictures per second made from 250 different figurines for 1 min and 20 seconds of film. In fact, the film contains 960 pictures.

B. *Tribute to David Bowie*

David Bowie died at the time Tibo Pinsard and Michaël Gauthier found a way to make the film happen, in early 2016, after a first attempt to make a microscopic film (that failed due to money and technological reasons).

Tibo Pinsard studied in art school, then started directing a documentary on Iggy Pop & the Stooges. David Bowie is one of his heros. The artist's death was a big shock to him, as it was to a lot of fans and music lovers. Stardust Odyssey is Tibo Pinsard's way to pay a tribute to the major figure Bowie was and still is. It starts with the title of the film itself: Stardust Odyssey, inspired by Space Oddity (which was inspired by Kubrick's 2001: A Space Odyssey [10]) [11] and Ziggy Stardust [12]. Many details of the animation short are references to the creative world of David Bowie. Such as the Blackstar (also a reference to Space Odyssey's monolith), also Bowie's final album. The film tells the story of a human character being born from stardust. He is feeling more and more alive the closer he approaches it, until… he changes again.

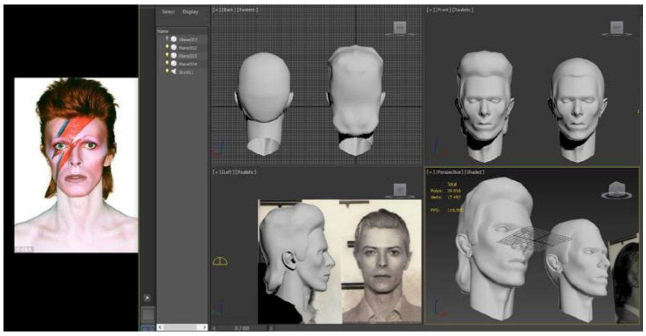

Figure 8. 3D modeling of the figurine based on a mugshot of David Bowie.

C. *A film and a world record*

Stardust Odyssey is not only a story or a tribute, it is also a technical challenge which consists in a world record validated by the Guinness World Records on November 13th 2019: the smallest 3D stop-motion animation character (300µm height) (see figure 9) [3]. The whole film including the behind the scenes documentary is available on line [1].

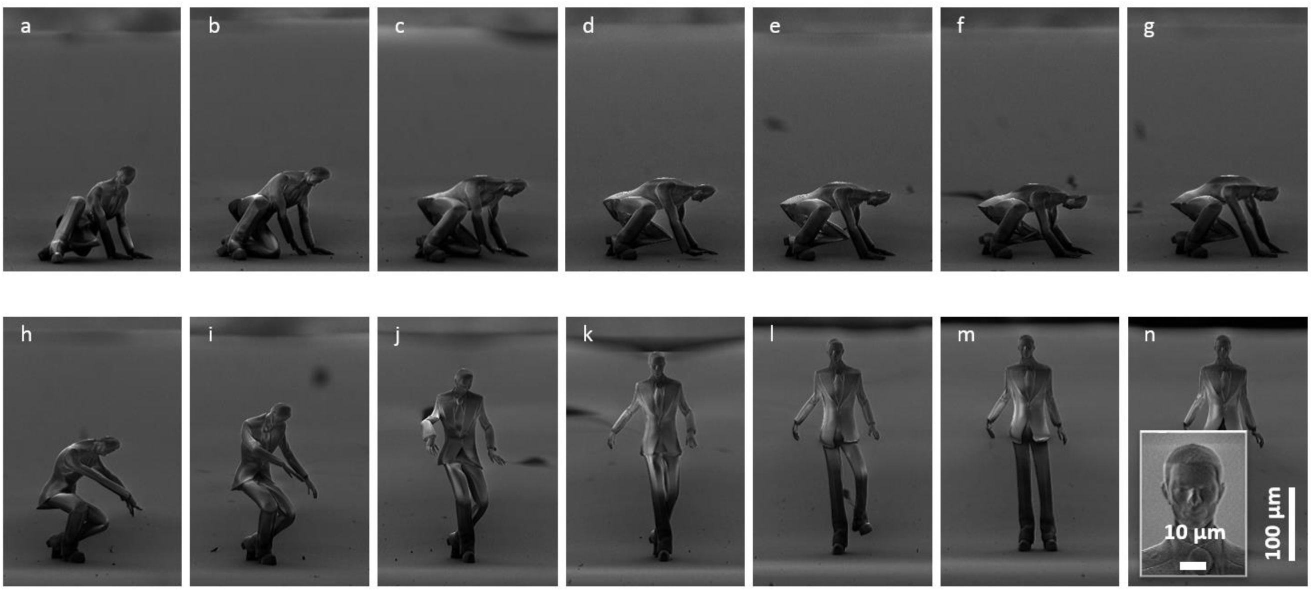

Figure 9. Images of the film: David Bowie gets up at the beginning of the film. The whole film including the behind the scene documentary is available on line [1].

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VI. Technological and Artistic Outcomes

This project that mixes high technologies and art enables to improve the technological know-how on 3D printing and high precision miniaturized robotics. During printing, the most important challenge was the impression of figurines that are cantilevered (arms and legs during walking sequence). The movement of the resin during the printing process may induce large deformations on the final printing figurine. We propose to print first vertical walls close to the figurine in order to reduce the movement of resin during the figurine printing. It enables to print highly cantilevered figurines such as the figurine described on figure 9(l). This know-how is now used currently to print microdevices and especially microgrippers [13].

The film has also provided new robotic capabilities by developing a complete software that enables to perform high precision positioning in a semi-automatic mode when the current SEM micromanipulators in the world is only teleoperated. This robotic control enables to perform various operations of robotic micro-assembly in various application frames [8].

As SEM provides black & white images, our film is almost a black & white film. It could be possible to add colors during post-production in order to obtain a color film. However, as this film is the first one enabling to discover microscale real world in 3D images, the audience is immerged in an amazing unknown world. The film maker would like to induce to the spectators the particular feeling of the discovery of a new space, new world mixing excitation, fear and curiosity. We consider that black & white images contribute to the strangeness of the film and thus contribute in some way to the audience's experience.

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