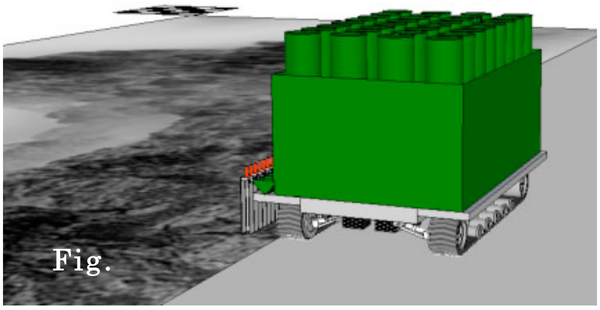
ALVARO CASSINELLI / 2011 / RESERCH PROPOSAL

Purpose of the Research (Outline)

The purpose of this research is to study a swarm of **un-tethered "robotic printing heads" capable of printing (or scanning) in parallel over large and/or curved surfaces**. These devices – either wheeled or flying robots - will facilitate printing in urban space (advertisement panels, signage, etc), as well as perform scanning of large, non planar architectural structures with a resolution never achieved before. The principles studied here could be extended and applied in the future to create an **"intelligent printing ink" composed of swimming nano-bots**.



Printing on large surfaces (e.g., advertisement panels on buildings or vehicles) involves today convoluted methods such as printing "strips" on a paper that will be collaged onto the surface. Even when this method is used, the largest strip achievable is much smaller than the final area, making alignment delicate. Also, printing is almost always restricted to *planar* surfaces, as there is no practical method to print on other shapes. The problem arises for two simple reasons: (1) it is much easier to move and track a printer head in a single dimension; and (2) the range of motion cannot be very large, something that is partially solved by the use of a long roll of paper. As a consequence, printing technology has been extensively developed in the printer-roll direction. Other methods – such as the plotter – have been of course developed beyond the table (see for instance [1]), but precise positioning of the printing (or scanning) head results in the need of a large, solid truss or a robotic arm, so that the final canvas cannot be very large.

Using tracking as well as sensor fusion and robot control strategies developed in our lab [2][3], **these limitations may not be justified anymore**: indeed, combining vision, inertial, optical, or magnetic tracking one can have **2d (and even 3d) high precision positioning, even on a very large area (or volume)**. Therefore, the goal of the present project is to demonstrate a **swarm of un-tethered robotic printed heads (RPHs)** that will be able to print in any kind of surface, whatever their size or shape. Using RPHs, **printing becomes a scalable parallel process.** If the print work has to be done in a very short time, one multiplies the number of RPHs: a hundred robots would make the work in a hundredth of the time. (This introduces a secondary motivation: that of making these RPH as small as possible, so that they will act more as photons than material particles – that is, they will not interact with each others in complex ways that imply path rerouting.).

Finally, this project will provide the technological basis for a large scale art project involving **printing of a football-field large image** using different types of rice husk, in collaboration with Professor/artist Romy Achituv, (WCU professor of New Media at Hongik University, Seoul) as depicted artistically in Fig.1).

[1] Gazeau, J.-P et al., "New Printing Robot for High-Resolution Pictures on Three-Dimensional Wide Surfaces," *Industrial Electronics, IEEE Trans.*, vol.58, no.2, pp.384-391, Feb. 2011

[2] Takeoka, H. et al,"VolVision: High-speed Capture in Unconstrained Camera Motion", The 4th SIGGRAPH ASIA 2011. December 12-15, 2011. Hong Kong, China.

[3] Yoshihiro W. et al, "Estimation of Non-rigid Surface Deformation using Developable Surface Model", 20th ICPR 2010, Istanbul, 2010, pp. 197-200.

Name of the research institution	The University of Toyko	Name of the Principal Investigator	Cassinelli Alvaro

Novelty and challenge of the research

Describe concretely and clearly focusing on the following points:
1) In what way does the current research have novel ideas and a challenging nature?
2) Elements which demonstrate that the current research will facilitate the development of new theories, novel ideas and will propose novel methodology […]

Fig.

As explained in the introduction, the goal of the present project is to **demonstrate parallel printing on large and/or curved surfaces using a swarm of un-tethered robotic printed heads (RPH)**. The most challenging aspect of this proposal is how to compose a coherent picture from the local printouts. What is needed is to maintain, at any time, a precise knowledge of the pose of the RPH, either with respect to a world reference frame, or with respect to the drawing being produced. (The second method is presumably the one used in the Nazca geoglyphs using simple surveying tools available at the time - Fig.2). Combining these methods will relax the constraints *in both*. As will be described next, we plan to develop sub-cm accuracy pose estimation strategies by using image based pose estimation to correct drift from other navigation systems, **as well as design distributed optimization algorithms to improve each robot "absolute" pose, using images of neighbor robots** as well as information exchanged wirelessly. More interestingly, in order to avoid artifacts in the image produced by a bad collage, we propose a "**jigzaw printing strategy" consisting on using features of the patches being printed** to guide each robot in "completing" the drawing - wherever they are (Fig.3). This would produce figures without printing artifacts (such as the lines produced by stripe-printing), but may have the effect of smooth, large scale deformations that can be corrected with less precise "global" positioning systems. Finally, **optical addressing** (i.e., projecting the pattern to be printed) could be used to cue robots (fitted with a single photodetector on their top) into actually print something or do nothing in a specific area, even if their motion is random - a strategy inspired by [4].

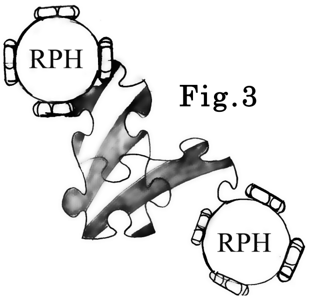


Fig.3

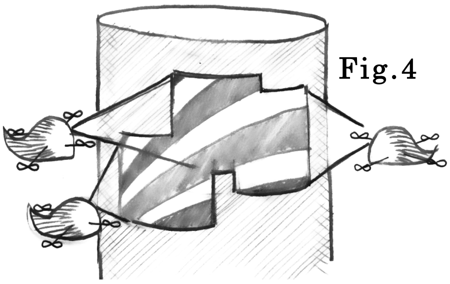


Fig.4

Apart from the study of distributed tracking and printing algorithm, we will explore several possible hardware implementations. This include **wheeled or climbing robots to print by direct contact with a physical surfaces**, as well as **contactless, local projection/scanning methods more suited for robots that move in 3d (such as flying drones)** for which maintaining a stable physical contact may be difficult. Indeed, the proposed "parallel printing" strategy could be extended for "parallel projection" using a **swarm of flying projectors** to compose an image over vertical or highly curved surfaces (Fig.4). Printing would even be possible by using spray or by "flashing" an intense beam over a photo-reactive surface as in [5]. It is interesting to note that in the near-future, a **swarm of microscopic nano-bots could be used to produce a print in parallel**, if ever they could know their relative position with high accuracy on a page; therefore, the study of these parallel algorithms (based on broadcasting one's own (presumed) global position, and adjusting it using more accurate, near neighboring tracking could form the base of a futuristic **"intelligent printing ink"** to print in two, or even three dimensions (there is a similarity here with morphogenetic gradients in developing biological organs). The converse of the robot printer head is the **robotic "scanning" head (RSH)**; the interest of a RSH swarm is that each robot could have a high resolution camera, so that the final scanned image would have a resolution never achieved before (picture-taking satellites are a particular example of this concept). This is in the line of previous work in our lab [6].

[4] Sugimoto M. et al, 'Augmented Coliseum: Display-Based Computing for Augmented Reality Inspiration Computing Robot', SIGGRAPH E-tech 2005.
[5]Hashida et al., "Photochromic sculpture: volumetric color-forming pixels", SIGGRAPH ASIA 2011.
[6] Toshitaka K. et al, 'Wide Range Image Sensing using a Thrown-Up Camera', IEEE ICME 2010, Singapore, 2010, pp. 878-883

Research Plan and Method

The applicant should provide details of the research plan and the methods for achieving the objectives of the research in a clear and specific manner, after succinctly summarizing it and providing an outline at the beginning. The plan should be divided into one for FY2012 and one for FY2013. The literature should be referred to as needed and main points highlighted. Moreover, where the research plan is being implemented by a group, indicate the specific roles of the Principal Investigator and Co-Investigators (*kenkyu-buntansha*) (using figures, tables and other visual aids) In case the research plan is being implemented together with Co-Investigators (*kenkyu-buntansha*), include the necessity and rationality of the project members, and the relationship to the purpose of the research from the scientific viewpoint. In addition, in order to clearly indicate the general view of the research group, state the roles of Co-Investigators (*renkei-kenkyusha*) and Research Collaborators [overseas co-researchers, company-employed researchers not eligible to apply for KAKENHI, graduate students and others (the names and the number of members may be stated)].

Research Plan and Method (Outline) **＊Concerning the Research Plan and Method to accomplish the Purpose of the Research, the applicant should succinctly summarize and describe in detail.**

We plan to conduct this research in several parallel directions: (1) developing a robust self-pose estimation strategy whose robustness scales with the number of RPHs; (2) develop the actual mechanical printer head (RPH); (3) study different distributed printing strategies.

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1) [FY2012-March to April] Single robot printer head & self-pose algorithms. In this first phase we will concentrate on steering a simple RPH, in the form of a holonomic, four or six wheeled robot. We have previously developed a simple wireless "turtle" robot capable of working as a vision-based "pantographic printing robot" (results yet to publish - Fig.5). It had a lot of drift because self-tracking was based simply on wheel speed integration, but it was the starting point of this proposal. Three things will be studied in parallel during this phase:

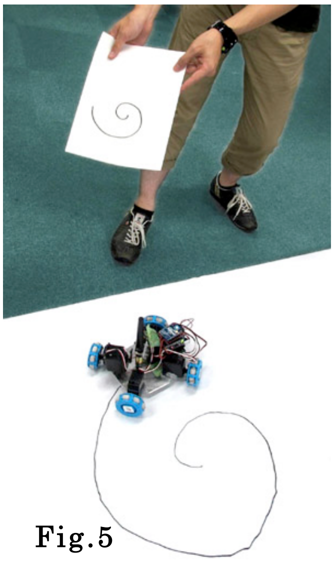

Fig.5

a) Improved tracking strategy. The goal will be to achieve very precise positioning of the un-tethered robotic printing head by combining external tracking (from a set of cameras in the room), with self-tracking (by using an inertial tracking unit, rotary encoders as well as an embedded camera). In these first tests, we will use special fiducial markers such as checkerboards (one on the robot, and several others on the room for letting the robot orient itself – akin to 'navigation by the stars'). All these tracking methods will be fused to correct drift and render pose estimation extreme robust and precise (sub-cm). Tracking accuracy will be verified at any time using commercial OptiTrack technology, which will not be used to orient the robot.

b) Displacement mechanism and printing route (including simulations). Holonomic motion may simplify path planning and re-routing. A robot with four or six "omniwheels" provides the additional advantage of being able to rotate over itself, which may be ideal to orientate a multi-pixel printing head (see below). As for the printing path, we will study both "vector graphics" drawings, and raster-scan printing. Even in this last case, the RPH motion does not need to follow a raster-scan path – and indeed we will consider several other strategies like sub-grid sampling and random sampling. This will be of use when several RPH will be working in parallel: **the pattern of printed blocks can serve as a navigation grid**.

c) Printing mechanism. To accelerate printing (and, as was briefly explained above, to produce printing "guides" usable by other robots), it is desirable to be able to print whole patterns at once instead of a single point at a time. We will first design an 8x8 printing matrix using ink or strong UV leds to test the system on phosphorescent paper or photochromic paper (as in the "pixel roller" project [7]). Depending on how precise we can perform tracking, we may consider integrating a commercial ink-jet printer head on the base of the robot, or even using a LED projector to project high-resolution image blocks on a photochromic paper as in [5].

[7] Hannes K. et al. 'Pixel Roller', Random International, 2005.

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Research Plan and Methods (continued)

2) [FY2013-March to Sept.] Team printing with multiple RPHs, This phase introduces really exiting new possibilities. A desirable feature of the tracking algorithm is that of becoming more robust as we add more RPH units. This problem is equivalent to that of optimizing the "extrinsics" of a set of cameras from a common "background" image - a well know problem in computer vision that would need, however, a powerful server computer. **Simpler strategies may be possible using just local computation from neighborhood images**. Using their embedded cameras, robots will be able not only to compute their *absolute* poses independently, but also see the fiducials on their neighbors, and compute their *relative* positions (Fig.6). Thanks to a low bandwidth radio network (or using infrared optical channels), they may be able to share the result of their "absolute" computation. Then, a distributed parallel optimization algorithm will be run on each robot, converging to a better estimation of each *absolute* position in the network (this bears some similarity to a SLAM algorithm [8], in which the "map" is changing over time, and correspond to the robot positions). The seconds strategy will consist **on adjusting pose and orientation by observing features of the printed patterns themselves** (i.e., the robots will orient and position themselves with respect to the drawing instead that with respect to a common "world coordinate frame"). **These "features" could be details of the image itself, the shape of the printing pattern (in the shape of QR-codes to be "completed" by other robots)**, or even temporary marks to be erased later (Fig.7). Both strategies imply that a **local coordinate system will be respected**, meaning that the robots could start printing in any part of the surface, and the drawing will not suffer from artifacts due to errors in orientation from each robot, even when the surface is not planar. Another interesting problem is how to optimize the printing process using several robots. There are a myriad of interesting possibilities, such as having robot "guides" whose purpose is to print a grid, take measurements, discover "dead pixels", etc. Mainly **for scalability reasons, we will concentrate uniquely on algorithms that run in parallel in every robot**, i.e., avoid "specialized" RPHs. Still, there are many problems to explore, such as were to start, and how to compose the picture. For instance, all the robots could start from the same location, check the figure already printed and "grow" from it; or they could each start in random locations, and grow regions until they connect (the first strategy may be preferred when local artifacts are tolerated, but not "global distortions"; the second strategy could be used in the opposite case).

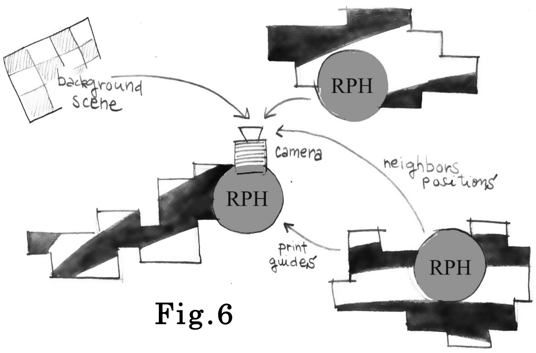

Fig.6

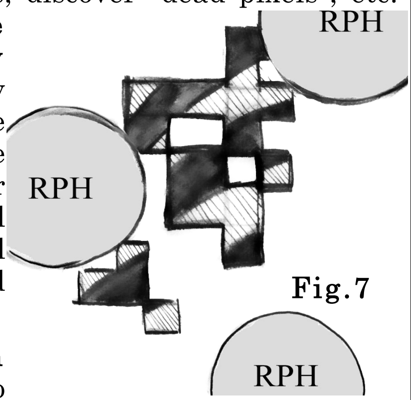

Fig.7

3) [FY2013-Sept. to April] Large scale demonstration on a football field. We will have a unique opportunity to demonstrate un-tethered parallel printing with RPHs on a football field in the framework of a collaborative artistic project with Professor Romy Achituv (HongIk university, Seoul). The most challenging thing here will be to design a large mechanical system capable of moving on grass, but **this part is already being studied and prototyped in his laboratory**. There is lately a revival of interest on "quadropter" flying drones [9] having already quite good on-board stabilization mechanisms – we will therefore try this strategy, although the flying robots will be only used to "print" on a planar surface. Apart from that, tracking and path planning strategies will remain unchanged. Of course, the specificity of the setup may dictate algorithm modifications – such as the fact that we cannot expect to have a large checkerboard in the field of view. In this case, natural image features (on advertisement panels or other stable structures) could be used to perform tracking.

[8] Hugh D. et al. , 'Simultaneous Localisation and Mapping (SLAM): Part I The Essential Algorithms;, IEEE Robotics and automation Mag. Vol.2, 2006. [9]: Fumiyuki S. (sphere drone), "Move freely! The world's first Spherical Air Vehicle", DCEXPO, MIRAIKAN, 2011. Also, commercial available AR Drone (http://ardrone.parrot.com).