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Portrait drawing by Paul the robot

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ABSTRACT

We describe Paul, a robotic installation that produces observational face drawings of people. Paul is a *naive drawer*: it does not have highlevel knowledge of the structures constitutive of the human face (such as the mouth, nose, eyes) nor the capability of learning expertise based on experience as a human would. However, Paul is able to draw using the equivalent of an artist's stylistic signature based on a number of processes mimicking drawing skills and technique, which together form a *drawing cycle*. Furthermore, we present here our first efforts in implementing two different versions of visual feedback to permit the robot to iteratively augment and improve a drawing which initially is built from a process of salient lines recovery. The first form of visual feedback we study we refer to as *computational* as it involves a purely internal (memory-based) representation of regions to render via shading by the robot. The second version we call *physical* as it involves the use of a camera as an 'eye' taking new snapshots of the artefact in progress. This is then analysed to take decisions on where and how to render shading next. A main point we emphasise in this work is the issue of embodiment of graphical systems, in our case in a robotic platform. We present our arguments in favour of such a position for the graphics community to reflect upon. Finally, we emphasise that the drawings produced by Paul have been considered of interest by fine art professionals in recent international art fairs and exhibitions, as well as by the public at large. One drawing is now in the Victoria and Albert museum collection. We identify a number of factors that may account for such perceived qualities of the produced drawings.

1. Introduction

The act of producing drawings from observation is a process that still elicits fascination. It is also considered to be a difficult skill to acquire. Paul is a robotic art installation developed by and based upon the style of artist–scientist Patrick Tresset in collaboration with Frederic Fol Leymarie. Paul produces observational drawings of people who pose in front of it using technologies and ideas developed in the context of the AIkon-II project at Goldsmiths, University of London, where we investigate the drawing activity through computational modeling and robotics with a focus on face drawing from life [1]. Although there are constant exchanges and overlaps between Patrick's art practice and the AIkon-II project, the aims are distinct: the former produces installations to be considered in an artistic context, whilst the latter is an investigation to be considered in a scientific context.

The drawings we are aiming to produce with an embodied system such as Paul are distinct from those made by a human hand, and yet it is our experience that they have comparable emotional and aesthetic artistic effects on the observer. We envisage that descendants of Paul that will benefit from further research efforts, such as those of the AIkon-II project, will be able to draw in manners increasingly similar to those of humans; however, we expect their styles to remain highly dependent upon a system's peculiarities, including physical and computational characteristics and limitations.

Paul was exhibited for the first time in June 2011 at the Tenderpixel Gallery in London, UK. Fig. 1 illustrates a typical gallery installation of Paul the robot. Since then, Paul has drawn more than 1000 members of the public, and over 200 portraits have been purchased. Paul has thus far been exhibited in the UK, the USA, Turkey, Italy and France (refer to Appendix A for details), and a portrait by Paul is now part of the *Victoria and Albert Museum*'s collection. These various events and exhibits have provided us with an extended range of critiques, comments and appreciations. Perhaps the most interesting feedback occurs when Paul is exhibited in a context where all other artworks are traditional: the reaction from drawing practitioners is always favourable, who invariably consider Paul's drawings as "working as drawings", in other words, as having the same qualities that characterise a good human drawing. A large proportion of the professional audience including curators, critics, collectors and artists also accepts and evaluates Paul's productions as artworks of quality.

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Fig. 1. Paul drawing Stella's face at the Tenderpixel Gallery, London, June 2011.

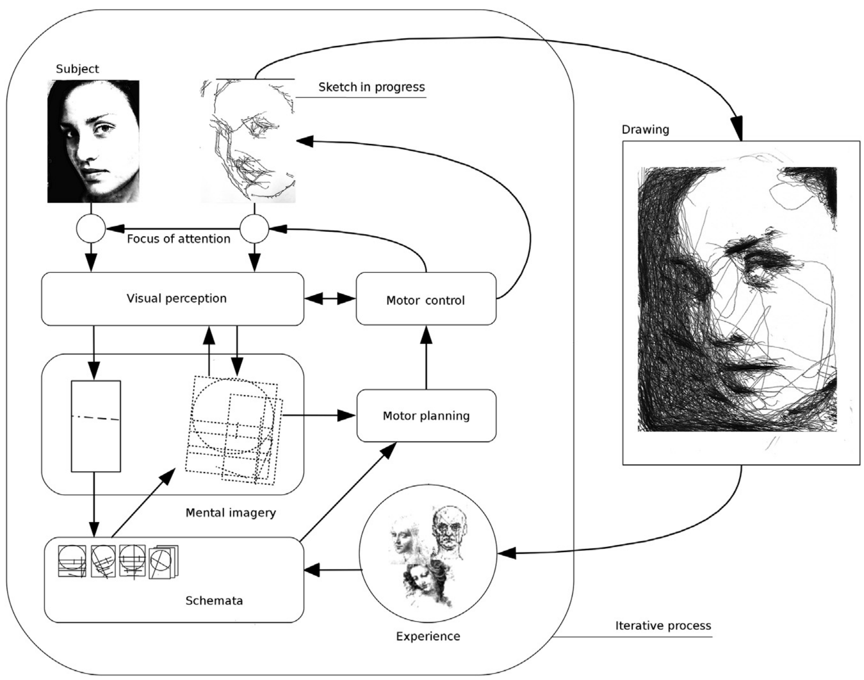

Fig. 2. A general system view on Alkon-II, a research project into the understanding and modelling of the face drawing activity. As an example of how visual perception feeds into mental imagery which can further trigger a schema, we illustrate on the left-hand side from the extraction of the pose of a face, a dashed line going through the eyes (in the mental imagery box), from which a specific schema can be retrieved, thus informing further the perception stage, *e.g.* in indicating what information to gather or check and where to expect it.

1.1. Research context for our work

Fig. 2 illustrates the main system components and their relation in the context of the research project Alkon-II. In this long-term project we explore the understanding and modelling of the face drawing activity. We have restricted our work to faces for two main reasons: (i) they play a very important role in the history of art and their depiction as artworks continues to exercise fascination; and (ii) faces are treated by the human visual system in particular ways, and this requires specific attention when modelling the artistic activity, *e.g.* faces as perceptual objects do not obey strict invariance under rigid body transforms: an upside-down face is hard to recognise and to read [2]. In addition, specific information about artistic techniques and methods used to draw faces ought to be considered, and eventually compared to ways of drawing other parts of the body or other types of objects. Furthermore, visual feedback specific to the observation of the face of the sitter and of the drawing being executed ought to be understood and modelled. Fig. 3 gives an insight in the use of visual feedback in our work by presenting two types of drawings produced by Paul the robot, while comparing these to the original motivation and style the artist Patrick Tresset had previously explored and developed.

We report in this communication our recent efforts in modelling aspects of visual perception, abstractions of mental imagery, motor planning and control, and how a sketch is gradually transformed into a final drawing. Future efforts should try to explore more sophisticated models of perception, mental imagery, and interactions with *schemata*. A schema is defined as concept and representation of, in particular, shapes, structures and information found in the world and integrated as knowledge about the world, as well as experience, *i.e.* learned knowledge specific to the task at hand [3]. In our case, schemata are to be specialised to faces, portraits and artistic drawing including styles and memory of previously accomplished artistic effects. Experience in turn can feed into the development of new schemata and

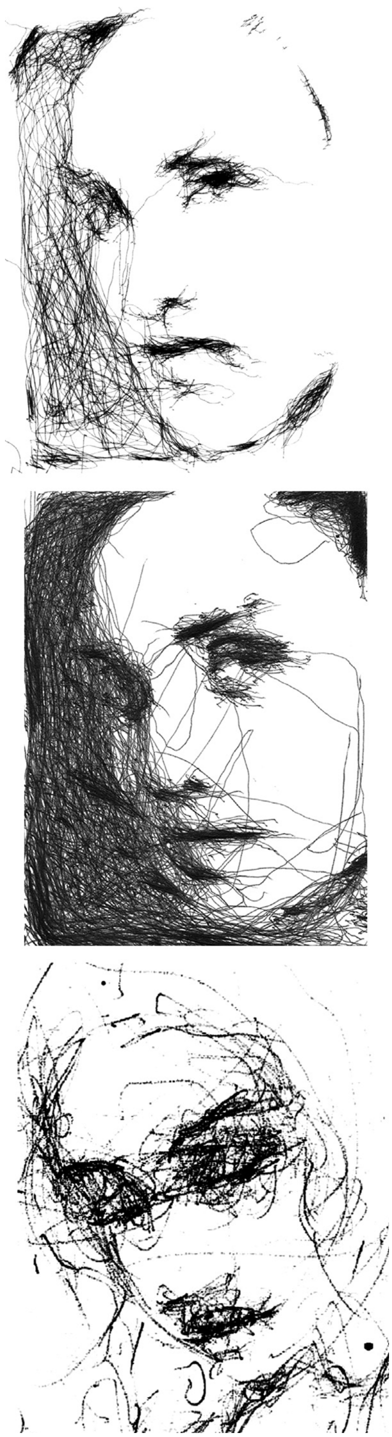

Fig. 3. Physical drawings of Stella by Paul, 2011 (cropped view): (*top*) with computational feedback only, and (*middle*) using physical feedback, *i.e.*, with additional snapshots captured of the drawing as it progresses (details in text in Section 3). (*Bottom*) Example of a drawing by Patrick Tresset, Pen on paper, 2003 (detail).

inform the drawing process as a whole. As an example of how visual perception feeds into mental imagery that can further trigger a schema, we illustrate on the left-hand side of Fig. 2 how from the extraction of the pose of a face, a dashed line going through the eyes (in the mental imagery box) is represented, from which a specific schema can be retrieved, thus informing further the perception stage, *e.g.* in indicating what information to gather or check and where to expect it.

In the next section we provide a short historical background and emphasise the position of Paul the robot in that context (Section 2). Then, we present a technical description and our latest experimental results on using computational and physical feedback mechanisms (Section 3). Finally, we discuss factors that may account for the perceived qualities of the produced artworks (Section 4).

2. Background

2.1. Art, machines and robots

Since the beginning of the twentieth century *mechanical machines* have entered the art world as subjects, objects, metaphors or evocations such as in the work of Picabia, Duchamps, Ernst and others [4]; yet, perhaps since Tinguely's inventions, other types of machines are present in the artistic landscape [5]. They exist more for what they do, how they act and interact than as objects to be depicted, and they prelude the entry of modern robotics in the art practice.

Today most research in robotics is geared towards creating utilitarian slave robots, such as those used in the manufacturing industry since the 1970s. Such robots may act in a relatively near future as soldiers, cleaners, builders, gardeners, drivers or even surgeon proxies. By contrast, robots invented by artists are usually anything but utilitarian.

Since the birth and death of the Senster [6,7], the large-scale sensual robotic creature designed and built by Ed Inahtowicz [8] and exhibited in the early 1970s at Phillips' Evoluon, the former science museum in Eindhoven, a significant population of robotic entities have entered the art world. This community is more akin to a zoo, a "*court des miracles*", a theater, than to a society of slaves, with such examples as *Le petit mal* by Simon Penny [7], *Sexed machines* by Paul Granjon [9], *RoboCoco*'s voyeur robots driven by curiosity [10], the *Robotic Action Painter* by Leonel Moura [11], or *Kismet* the social robot by Cynthia Breazeal [12]. Noticeably, each of these specimens stays well clear of the "uncanny valley" [13,14] by not attempting to look and act as human replicas. Yet, due to their movements, interactions and reactions, the human audience tends to express empathy and will respond to these simple creatures as if they were alive.

Where does Paul stand in this context of art mixing with robotics? Paul is an obsessive drawing entity and alike many of its contemporary robotic artworks it does not attempt to emulate human appearance (Fig. 1). But Paul produces new artefacts and like its utilitarian slave siblings it, too, can replace, with more or less success, the human, this time in a particular creative activity, that of drawing faces.

2.2. Art, computers, graphics and robots

There are many examples of computer systems attempting to artistically draw from *reality*. This is most prominent in computer graphics in a sub-field referred to as *Non-Photorealistic Rendering*, or NPR, which started to grow in the 1990s [15–20]. NPR systems typically produce approximate renderings extrapolated from reality, usually by taking digital images or 3D models as input. The majority of these systems have thus far been designed to render drawings or paintings in a particular style by producing output images mimicking a *final* result with relatively little attention paid to the creative steps involved in the artistic generation itself: *i.e.* how, as Zeki formulates it [21], the artist extracts permanent, lasting and enduring features from a visual stimulus forming a novel presentation of the original subject. However, Hertzmann argues that NPR ought to produce theories of art focusing on the creative and generative processes [20].[1] We too have in our past [22] and current [23,1] work attempted to achieve such a goal and have further taken the step to pursue an *embodiment* of the modeling of such processes via robotics. We take the view that this is a promising avenue of research if one's goal is to better understand and mimic biological systems, including the human artist at work, for which behaviour is a function not only of their neural or computational system, but also of their morphological capacities and of their interaction with a surrounding physical environment [24].

The pioneering work of Harold Cohen with his AARON system [25,26] is probably the best-known example in which a *model of the artist's activity,* whilst drawing/painting from *imagination,* has been studied, implemented and refined over the years since its inception. While Paul is conceived to produce drawings based on visual perception, AARON does not consider visual inputs. Early versions of AARON were embodied via robotic platforms; this was later abandoned by Cohen who found that in exhibits, the robotics aspect of AARON was getting too much attention in place of the produced artworks, the drawings [26, p. 84].

Since AARON, a small number of robots dedicated to drawing and painting have been developed by artists, roboticists or computer scientists. Most of these robots operate in an open loop manner, *i.e.* without comprehensive feedback mechanisms that map inputs to outputs. An early and interesting attempt at creating a robot portraitist is to be found in the works of Calinon et al. who conceived of a robot verbally engaging with a sitter ("give me a pen please") and which was based on traditional computer vision routines, without attempting to model the artistic processes themselves [27]. To our knowledge, only very few other recent projects use visual feedback to control the robot's execution of the drawing. Leonel Moura, in his Robotic Action Painter experiments and exhibits, has physical (visual) feedback controlling the behaviour of simple mobile platforms carrying coloured pens [11]. Visual feedback provided by a grid of nine overhanging cameras is used to determine when enough colour has been imprinted on the canvas upon which the robots navigate. Lu et al. report on their experiments with the Intelligent Robotic Art System (IRAS) to produce pen and ink drawings based on digital images [28]. They use visual feedback to assist the hatching process by controlling the placements and orientations of the strokes. The painting robot eDavid by Deussen et al. can use various media from ink to oil paint [29]. The system also relies on a camera to gain visual feedback from the painting in progress. In their early experiments this feedback is used to optimise stroke placements during the application of a monochromatic paint. The current system works by simulating an initial target image constructed via an NPR method of "painterly rendering" [18] and relying on a grey-level input image. This target image is compared with the image of the artefact painted on the canvas. A new set of brush strokes are planned in a manner to reduce differences between the target and the current state.

With Paul, two types of feedback are exploited: (i) *computational* via a purely software-based implementation and (ii) *physical* exploiting the camera as an eye observing the drawing being rendered. This is described in detail in Section 3.6.

3. System description

3.1. Installation

Paul is composed of a left-handed planar robotic arm, with a black Biro pen as end-effector and an actuated pan and tilt webcam attached to a vertical wooden stick bolted to a table, all controlled by a common laptop computer. On one side of the table is a chair. Always present at the installation is a human assistant: their role is to change the paper and give the signal to Paul that a subject is ready to have their portrait executed.[2] The assistant may also give directions to the sitter and adjust the light. When the location allows it, unsold sketches are displayed on the wall around or behind the installation (Fig. 4). In addition to the drawing cycle, Paul also performs a number of behaviours that are only pretenses. These actions are implemented to entice the audience into believing that Paul is more alive and autonomous than it actually is, and they reinforce the relation between the sitter and Paul. For example whilst drawing, Paul often takes a look at the sitter, scanning the face with multiple saccades and fixations. In reality Paul draws from a single picture of the sitter taken at the initial stage of the production cycle. However, Paul's eye also follows the movements of the pen during the drawing phases as a human drawer would do. Such new image feed is used when considering physical feedback for shade rendering (Section 3.6).

3.2. Hardware

Paul is a robotic hand–eye system solely dedicated to the drawing activity. To remove as much complexity as possible we have constrained the arm's configuration to that of a three-joint planar arm, with an extra joint to allow for lifting or bringing the pen in contact with the paper (Fig. 5).

Traditionally radio controlled (RC) servos have been used as actuators in DIY robotics and low-cost research projects, but they present numerous drawbacks, such as not providing any feedback, or the need to have one dedicated wire for each servo. An interesting alternative are smart servos such as the Dynamixel AX-12 series manufactured by Robotis [30]. Each such servo includes an integrated 8-bit micro-controller and is addressed with an 8-bit ID that can be networked in a daisy chain. Commands are sent by writing some values in registers, while servo states (for feedback) are queried by reading these values. Commands include position, velocity, compliance and maximum load. Feedback includes position, velocity, load and voltage. Furthermore, the associated construction kits are very well designed. For these reasons we have chosen the Dynamixel AX-12 for Paul's construction. Even if the specifications of these servos are rather impressive, they remain low-cost actuators. As such they present some drawbacks including a relatively low resolution and low feedback frequency. The resulting lack of precision causes *disparities* between the path planned and the path executed by the arm, which, in itself, can be seen as *part of the signature and style* of Paul.

3.3. Robotic control and software architecture

Contemporary robotic software architecture is based on communicating concurrent distributed processes. In recent years we have seen the development of open source middleware dedicated to robotics such as ROS (Robotic Operating System) [31] and YARP (Yet Another Robotic Platform) [32]. These frameworks help to organise and manage processes and communication between sensors, processors and actuators. Advantages of these frameworks include that they facilitate the reuse of components and have a large ecosystem of research teams that use these and continuously publish new components reusable for other

[1] Hertzmann provides an excellent recent overview of the field [20], where he emphasises how NPR algorithms mainly model the "mapping from inputs to outputs" rather than the "processes by which an artist" operates.

[2] Both of these tasks by the human can be automated and we have experimented with previous designs allowing for full automation: *i.e.* handling the paper feed and detecting the presence of a new sitter.

Fig. 4. Paul the robot at Neo Bankside, part of the Merge Festival, London, October 2012.

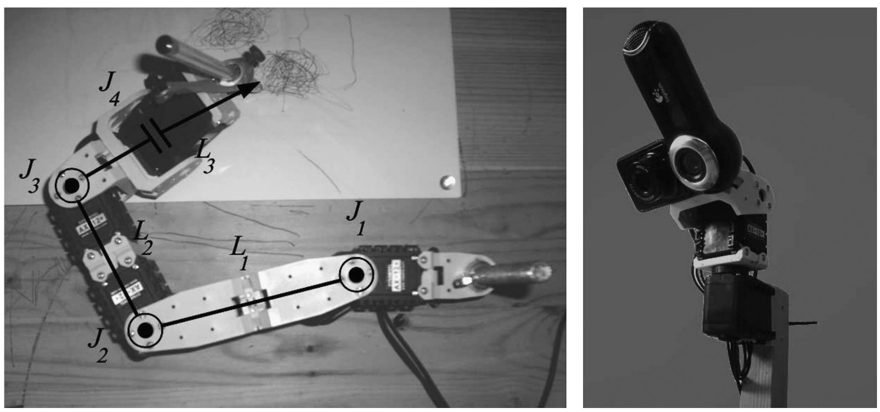

Fig. 5. Details on Paul's arm and eye. Left: View from above of: shoulder (J1), elbow (J2), wrist (J3), hand (J4), upper arm (L1, 108 mm), lower arm (L2, 88 mm), fingers with pen (L3, 110 mm). Right: camera/eye actuated with 2 degrees of freedom in orientation.

projects. For historical reasons,[3] Paul's control software is built using the YARP framework. The main communication elements of our software architecture are summarised in Fig. 6.

3.4. Drawing cycle

The high-level overview of the set of steps Paul goes through in order to complete a drawing can be summarised as follows:

1. Localise the sitter by moving the camera until a face is detected and focus the camera onto the sitter's face.
2. Take a picture, limit it to a region of interest, convert it to a grey-level image and apply a contrast curve.
3. Draw salient lines.
4. Perform the shading behaviour.
5. Execute the signing script.

Once the execution of the drawing is completed, Paul is in waiting mode until the human operator gives the signal to the robot to initiate the next drawing sequence, either by (i) covering the camera lense for 10 s, (ii) moving the arm, or (iii) knocking three times on the table (uses a microphone). Paul is essentially *autonomous* although three steps have been left under the control of a human collaborator to: (a) guide a calibration routine which is executed only once, when installing the robot in a new location,

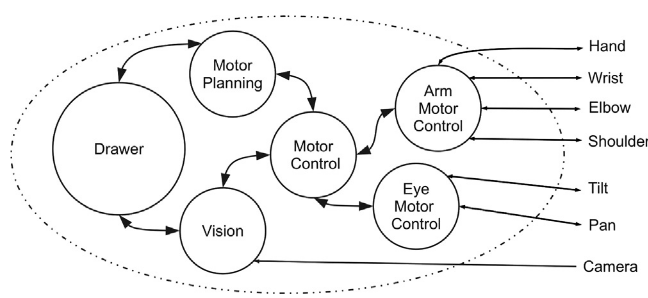

Fig. 6. Software architecture. Drawer ↔ Motor Planning: Drawer sends instructions such as: draw a spline going through this set of points; Motor Planning sends a message back when the line has been drawn. Drawer ↔ Vision: Drawer sends instruction such as: look for face; the Vision process sends back a cropped image of the face. Vision ↔ Motor Control: used for the "eye following pen action". Motor Planning ↔ Motor Control: sends the movements to be performed by either the arm or eye; sends back info when movements have been executed. Motor Control ↔ Arm Motor Control and Motor Control ↔ Eye Motor Control: from high-level control to low-level device control; sends back servo positions and if they are still moving (movement finished or not).

e.g. at the start of an exhibit, (b) change the paper, and (c) give the starting signal of a new drawing cycle. Each of these three tasks can be automated if desired without great difficulty.

Below we provide the main details for steps 1, 3 and 4 of the above drawing cycle. Note that contrast curve adjustment (part of the calibration) is only performed once per session (per installation of the robot); hence it is not critical to the cycle: the same curve adjustment proves useful for a multitude of portraits in a typical exhibit or performance.

[3] We participated to the Barcelona Cognition Brain and Technology (BCBT) Summer school in 2009, where YARP was first introduced to us. The development of our first generation of robot drawers soon followed.

3.4.1. Face localisation

We rely on the well-known OpenCV object detection library [33] for our implementation of face localisation, which provides the Viola and Jones' detector [34] as improved by Leinhart [35].

3.4.2. Salient lines extraction

Lines are first extracted from the result of the convolution of Gabor kernels [36] at multiple orientations with each level of a *pyramid representation* of the sitter's image [37,38]. The pyramid representation is used as a good approximation of how an artist processes an image at multiple levels of resolution to capture smaller and larger features (here derived salient lines). We have found that in practice four levels of a pyramid is sufficient for our purpose of extracting sets of salient lines at a range of discrete resolutions and orientations.

Once the face is localised, we take a cropped view centered on the face with a height:width ratio of the cropping window equal to a 1.45 proportion. This is based on the experience of the artist (Tresset) who has judged such a proportion leading to good (aesthetically pleasing) results without being strictly based on other well-known metrics such as the golden ratio (circa 1.61). This cropped view is taken as the basis of the image pyramid and always set to the size 320×464 pixels. Then, the other levels are built by successive simple averaging at sizes 160×232, 80×116, and finally 40×58 pixels. Beyond this, the image resolution is too coarse to be useful to extracting salient lines. Once the pyramid is built, basis to top, we process it from top to bottom to extract lines at increasing levels of detail.

A visualisation of the process at (top of pyramid) level $L=3$ is presented in Fig. 7. We make use of the classical Gabor kernel, g

$$g_{\lambda,\theta,\varphi,\sigma,\gamma}(x,y) = \exp\left(-\frac{x^2+\gamma^2 y'^2(\theta)}{2\sigma^2}\right)\cos\left(2\pi\frac{x'(\theta)}{\lambda}+\varphi\right), \quad (1)$$

where $x' = x\cos\theta + y\sin\theta$, $y' = -x\sin\theta + y\cos\theta$, $\gamma = 0.5$, $\lambda = 5$, $\sigma = 2.5$, $\varphi = \pi$ [39].

Each oriented Gabor kernel models a receptive field of simple cells in area V1 of the visual cortex. Each such Gabor kernel takes approximately the shape of an ellipse (in spatial extent) with eccentricity determined by the spatial aspect ratio γ. Petkov recommends a value $\gamma = 0.5$ [39]. The angle θ specifies the orientation of each kernel (with respect to the axis x). The parameter λ measures the wavelength of the harmonic factor $\cos(2\pi(x'/\lambda)+\varphi)$ in Eq. (1), where the phase offset φ determines the symmetry of the Gabor kernel g. A value of $\varphi = \pi$ ensures a symmetric kernel with respect to the receptive field centre. The ratio σ/λ determines the number of parallel excitatory and inhibitory zones in a receptive field. Petkov recommends a value $\sigma/\lambda = 0.5$ [39]. The linear size of the receptive field is determined by σ, such that at distances 2σ and beyond, from the centre of the Gabor g, the receptive field has no more practical effect when convolved with an image.

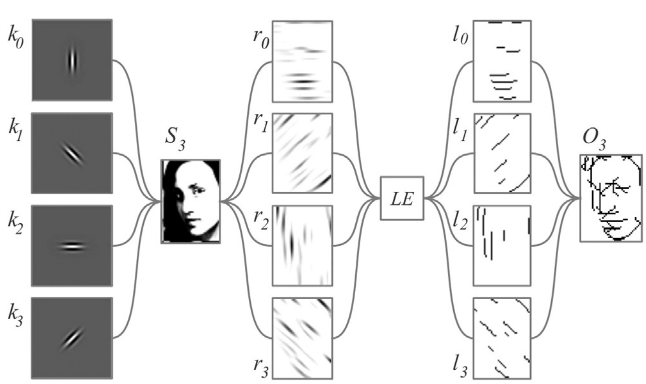

Fig. 7. Salient lines extraction at level $L=3$ (the top of a pyramid). S_3: Sitter's image at size (40×58) pixels, level 3 of an image pyramid. r_h: Results of the convolution of *set* $K(3)$ $(h=0,1,2,3)$ with S_3 (for readability, in this illustration the image's grey levels are inverted). l_h: Visualisation of the lines extracted from each r_h as a result of the line extractions process, *LE*. O_3: Visualisation of the combination of the line sets l_0, l_1, l_2, l_3.

First, at the top level $L=3$ we build a set $K(3) = \{k_h\}$, with Gabor kernels at 4 orientations $[\theta = h \times \pi/4,\ h = 0,1,2,3]$. At the remaining levels of the pyramid, *for* $L = 2,1,0$, we build sets $K(L) = \{k_h\}$, each with kernels at 8 orientations $[\theta = h \times \pi/8,\ h = 0,1,\ldots,7]$.

For each pyramid level, the results of the convolution with oriented Gabor kernels are considered for a Line Extraction (LE) process as follows. Initially each resulting image is brought back to original image resolution using bilinear interpolation. Then, each such oriented image is thresholded to isolate elongated regions called blobs. A blob is defined as a 2D array of connected pixels (a connected component after thresholding). Elongated blobs are used to approximate salient lines in an image at level L — the threshold for each level has been determined empirically to obtain good blob separation.[4] Second, connected components (of the blobs) are extracted from the binary results (in our case, using a common routine from the Python library Gamera [40]).[5] Third, a 2D medial axis transform [41] is applied to each blob such that the longest axial branch is kept. The medial axis has proven to be a good way to approximate how an artist like Tresset plans his gestures to trace the length of salient lines (and cover other regions for shading) [22,42]. Fourth, each medial axis branch is then represented by an array of points to be sent to the *Motor Planning* process which is then used by Paul to draw salient lines (Fig. 8).

The use of Gabor kernels to extract lines is motivated by a number of factors:

- Biology: Gabor kernels are commonly used to model image edge responses in the primary visual cortex, in humans and other mammals, to variations in frequency and orientation [43,44].
- Stylising effect: as a discrete number of orientations is used, the curves are constructed from lines for a limited set of orientations. This limitation is a distinguishing feature desirable in hand drawings [45]. In the same manner as a restricted colour palette is used in a painting, this reduced orientation palette has stylising (a simplification of good aesthetic value) and harmonising (the lines work in unison) effects.
- Related to the manner curves are measured to be depicted: one common manner in artistic drawing to measure observed curves is to imagine/visualise the tangents. Such tangents are drawn lightly or visualised (imagined) and used as construction lines.
- One of the effects of using Gabor responses is that salient portions of curves (with higher curvatures) are accentuated as we combine the responses. This is desirable as high curvature regions including corners and junctions are important in providing facial shape information, and this improves the drawing's readability. Furthermore, having curves depicted in

[4] NB: In general, when we need to decide on a threshold value, this is based on trials and errors with an initial set of test images in the lab. and then set definitively for all remaining experiments. This is satisfying for us as we do not seek great levels of accuracy in the final results obtained, which is not the purpose of the stylistic signature we are studying here: *i.e.* we remain distinct from photographic portraiture.

[5] http://gamera.informatik.hsnr.de/: The Gamera Project is a toolkit for building documentation recognition systems. We have mainly used the connected component routine `cc_analysis()` and the `medial_axis_transform_hs()` routine from which the MA topology (including the number of branches) can be retrieved via the `skeleton_features()` method.

Fig. 8. Example of the extraction of salient lines: cropped original on the left and final combination of salient lines drawn by Paul on the right (cropped view scanned from the drawing on paper).

a non-uniform manner adds to the interest of the drawing by having locally greater variations.

Once salient lines are drawn by Paul, we proceed to the next step in the drawing cycle, that of shade rendering.

3.5. Shade rendering

In the context of rendering shading during the drawing process by artists, a range of different strategies exist. All rely on a progressive set of steps using visual feedback for control. Our visual perceptual system has some peculiar features such as contrast and colour constancy.[6] These features present drawbacks when attempting to draw from observation as, for example, contrast constancy prevents us from being able to evaluate tones in the absolute; in other words, we can only evaluate tones relatively. When using a single pen, shading is an additive process and thus if some parts of the drawing are too dark it is not possible to make them lighter. The tonal curve of the drawing is therefore different from the tonal curve of the perceived subject. Other transformations may also exist such as geometric distortions. With these constraints in mind, multiple strategies are used to render shading.

Shading generally consists of filling an area with patterns at different scales and concentrations. If the pattern has a perceptual orientation, it has to be related to the direction of the plane being depicted. If the pattern used has no dominant perceptual orientation, only the gray levels are represented. Often drawers take advantage of human visual limitations by rendering a discrete number of grey-level shades that will be perceived as a smooth gradation from dark to light. The number of grey-level shades depicted with such a strategy varies, but often five values are rendered: white (absence of pattern), light gray, mid gray, dark gray and black. We will use this strategy later in our *computational* version of *feedback*.

[6] This ensures our ability to (i) perceive objects as maintaining a constant contrast independent of size or distance, and (ii) perceive object colours as remaining nearly constant even under drastically changing illumination, *e.g.* from sunlight to artificial light.

In terms of the techniques used to render each shade area there are two main methods: pattern layering and non-overlapping patterns of various densities. The former enables perceptually smoother shading, whilst also giving the drawing a blurry effect similar to sfumato, one of the classic rendering techniques from the Renaissance era. The technique applied for overlapping shading is relatively simple: first a very light tone is rendered through tracing a sparse pattern, then progressively darker tones are overlaid. During this process the artist evaluates tonal values and contrast to plan for the next pattern layer to be rendered. Refer to Fig. 9 for a diagram representing the feedback loop controlling the overlapping shading process. We will use this strategy later in our *physical* version of *feedback*.

We further note that in practice the shading process, when performed by an artist, is informed by knowledge and experience, especially when depicting a known object such as a face in a common orientation and lighting. A human artist would also differentiate between cast and form shadows and render them accordingly. A general practice when drawing an object such as a face, is to not concentrate on a feature at once but to work on the face "as a whole" such that the detailing of each feature progresses in synchrony, with the face/head outlines being considered concurrently to smaller features such as nose, mouth, eyes, eyebrows.

At present, our working versions of Paul have no semantic knowledge of what a face is: *i.e.* we do not make use of the knowledge of features such the eyes, mouth, nose line, *etc*. In the following experiments on *feedback* we assume that the theoretical drawer we are simulating has no knowledge of the face structure, features and volumes: *i.e.* the artist only knows how to make a pattern that will be perceived as a shade of gray. In other words, our current simulation is that of a *naive drawer* [46,47].

3.6. On feedback

We now describe behaviours for shade rendering using two different types of feedback: computational (or internal) feedback and physical (or external) feedback.

Computational feedback (internal): A computational model of part of the drawing cycle is used via software to process information in a feedback loop.

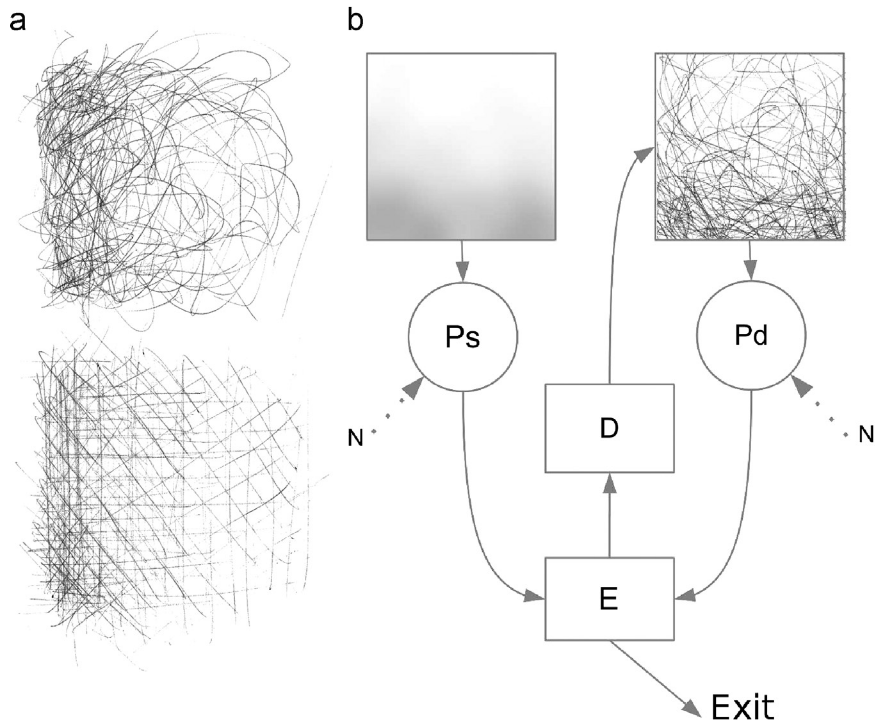

Fig. 9. Shading process: (a) Two examples of non-directional overlapping shading process. (b) Visually controlled shading process, where Ps represents the process of "Perception of the subject" and Pd is the "Perception of the drawing". There are two implicit perception modes: for action and for evaluation (analysis). Box E represents the "Evaluation" process where one compares the subject and the current state of the drawing to plan the drawing action. Within box E we also evaluate if the drawing is close enough to the target: the perceived subject with a different tonal curve. Box D represents the "Drawing planning action" and N stands for noise to the system.

Physical feedback (external): Here the system uses data from an external source, such as a camera, as new (sensory) input for a feedback loop.

In theory, with a sufficiently precise simulation of both the drawing processes and robot actions it would not be necessary to use external visual feedback from sensors such as a camera. However, our early experiments with physical feedback are motivated by a number of factors and important ideas:

- We are establishing an integrated hardware and software framework that enables us to pursue further research questions about the various processes involved during the face drawing activity. We are interested in better understanding how embodiment of at least some of the processes plays a role in humans' capacity to draw, possibly explaining limitations. Using an articulated arm mimicking that of a human limits the ways in which line gestures can be performed and sequenced. Positioning in space a physical camera–hand system imposes combined limits on viewing angles, distances to the sitter and canvas, as well as lighting — as is the case for a human artist. Different potentials for drawing emerge and the strategies that are put in place are not necessarily easily derived if one operates in the purely software-based context, where the greater freedom in the design does not offer the same strong guiding principles as a bio-inspired physical design [24].
- The detailed (software) simulation of the drawing activity becomes increasingly complex and less flexible as we refine our attempts to integrate the various processes that are part of the drawing cycle (Fig. 2). For example, a system using visual feedback from a camera does not necessitate a change of software parameters and modelling routines when changing the pen or paper, or even part of the arm. The addition of other modalities, such as via haptics or pressure sensors, can be performed once such devices and their associated softwares are made available. In contrast, a system using (only) a software simulation would necessitate either human intervention to adapt to these types of changes, or the additional modelling and simulation of these new tools, with a sufficient understanding of their physical properties.[7] Furthermore, a physical environment itself changes dynamically: *e.g.* sunshine emerges from the clouds, someone moves the robot slightly, some passerby is momentarily casting a shadow on the canvas, the paper is not always firmly pinned down. Such dynamical events, mostly random in nature, make for a richness in the outcome of each drawing session. A careful simulation hence becomes somewhat ineffective.

In the remainder of this section we describe how both feedback schemes have been implemented. Remember that both methods follow the preceding salient line step and thus start from an initial drawing of these lines by the robot. They both then refer to the original snapshot of the sitter to perform feedback evaluations before drawing additional lines on the canvas to render shading.

3.6.1. Shading behaviour with computational feedback based on blob cover

The following strategy produces non-oriented overlapping patterns and takes into consideration possible concavities, bays, inlands and holes. The sitter's image is thresholded at four

[7] It proves in practice very challenging to model and simulate accurately factors such as: (a) the dynamic properties of the servos, including torque, velocity, positional accuracy, inertia and changes in characteristics due to wear/aging; (b) the complete actuated arm and its dynamical properties; (c) the change in dynamics due to the friction of the pen on the paper, which depends on pen pressure, the paper's rugosity and texture, and the type of pen used; (d) the specific characteristics of the ink on the paper.

Fig. 10. From salient lines (left) to a final drawing (right) with shades rendered via *computational* feedback. NB: these are scans of drawings done on paper by Paul, and the scaling and cropping are not exactly the same.

different levels providing five binary maps. The map corresponding to white regions is then discarded. For each of the four remaining maps, an array of connected components (blobs) is extracted.[8] For each blob a set of points is chosen from which a cubic spline is interpolated. The points are chosen randomly one by one to form a set sampling the blob and its vicinity. From an internal model of the blob (a two-dimensional binary array), visual feedback is used to evaluate if the latest chosen point should be added to the set or if another point should be randomly considered. Criteria for evaluation are: (i) the distance between the two last points should be less than a value that is proportional to the blob's size, and (ii) the percentage of the trace (of the line segment between the two last chosen points) that lies outside of the blob should be under an *a priori* selected threshold value. The first criterion (i) is to avoid a shading pattern having lines that are too long, while the second (ii) is to make sure that the pattern does not cover concavities, bays, inlands and holes. The search for new points is interrupted when the length of the path going through all the considered points in the set reaches the stopping criterion, a value proportional to the grey-level currently considered and the blob's area size. This gives the drawn pattern a tonal value equivalent to the targeted grey-level. The interpolated path is then sent to the motor planning routine.

Visual feedback then detects if a relatively large area of the model of the blob has not yet been covered by path traces, which triggers a new line drawing step for this smaller sub-area now considered as a new blob. This way of randomly selecting points for splines was experimentally found to give a good approximation of the way the artist (Tresset) draws lines when rendering shades of gray patterns. In Fig. 10 we compare the initial state of the process — the salient lines drawn by Paul taken as iteration 0 of the shade rendering — with the final drawing following shade rendered via computational feedback. Four more portraits using computational feedback are shown in Fig. 11.

3.6.2. *Shading behaviour controlled by physical feedback*

A diagram of the shading process when using physical feedback is presented in Fig. 12. We now provide details on each operation applied in the feedback loop.

[8] We make use again of the Gamera routine `cc_analysis()`.

Pd: Perception of the Drawing. In the current setup, images of the drawing are captured with a Labtec Pro9000 camera.[9] Due to its position in space, usually making some angle with respect to the drawing plane, some specific processing is also necessary (via an homography). Below we give details on the 3 main steps under Pd, that of "undistort", "homography" and "filtering".

- Undistort:
  Due to the physical properties of the camera lens, captured images present two main types of distortions: (a) radial, that are due to the spherical shape of the lens, and (b) tangential, that are caused by the plane of the lens not being perfectly parallel with the sensor's plane. It is possible to correct these distortions through a two-stage process: (i) a calibration stage that measures the intrinsic camera characteristics, and (ii) a computational stage that uses these characteristics to undistort the images.[10]
- Homography:
  Another source of systematic distortion is due to the position of the camera plane in our setup which is not parallel to that of the drawing. A two-step process is employed to undo this projectivity and rectify the image: (a) calculating the homography matrix with two sets of points from the two planes; and (b) applying a perspective transform using the computed matrix. An illustration of our use of this implementation (combined with the "undistort" process) is provided in Fig. 13.
- Filtering:
  When we perceive shading patterns at a distance we do not perceive the individual lines that constitute the pattern but instead a gray area. To simulate this phenomenon we have experimented with a number of

[9] The labtec Pro9000 by Logitech is often used in low-cost research experiments due to its characteristics: good lens, relatively high resolution, good frame rate at high resolution, low compression.

[10] We make use of the OpenCV library routines to measure these intrinsic characteristics [33], essentially by evaluating distortions when capturing multiple views of a known (chessboard) pattern.

Fig. 11. Four signed portraits by Paul, using computational feedback for shade rendering in addition to initial salient lines (cropped views), 2011.

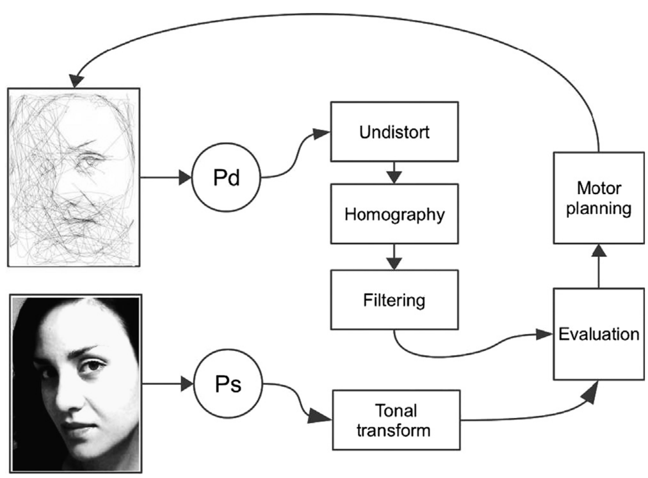

Fig. 12. Implemented shading process with physical feedback (details in main text). Reminder: Ps represents the process of "Perception of the subject" and Pd is the "Perception of the drawing".

filters, including: uniform, median, Gaussian and bi-lateral [48]. In the current implementation a combination of uniform and Gaussian filters was selected, leading to satisfying results. The parameters of the filters are set through prior experimentation and hard coded. However, we have recently experimented with an implementation that dynamically sets the parameters using an internal feedback loop which looks promising; in the future this shall permit the robot to have greater autonomy to adapt during the drawing process and also adapt when using varied drawing devices (pens).

Ps: Perception of the subject. This is currently implemented via one main step, that of a tonal transform.

- Tonal transform:
  In sketches, drawing and paintings the tonal representation is different from what we perceive or what is recorded from a camera with limited sensitivity. This transformation of the tonal range in drawings is a characteristic that has a considerable impact on style and aesthetics. In the current implementation this transformation is executed via a contrast curve manually set as an initial calibration step at each location where Paul is exhibited depending on the ambient lighting.[11] We are currently experimenting with an adaptive algorithm with internal visual feedback that will allow the autonomous computation of the contrast curve to be applied to the input image.

Evaluation: The evaluation is currently a simple subtraction of the processed (filtered) drawing image from the subject image that produces an error image. The resulting image is fed back into the shading process described in Section 3.6.1, but this time, instead of having the input image thresholded into a five-level layered map, only one level is extracted at a high threshold (*e.g.* 200 on a 255 grey-level range) to recover darker areas, ignoring remaining lighter tones. This process is reiterated until the shading process only draws a number of lines under a user-specified desired maximum. In Figs. 14 and 15 is presented a visualisation of the process at various stages.

In Fig. 16, in similitude to Fig. 10 for the computational version of visual feedback, we compare the initial state of the process — the salient lines drawn by Paul taken as iteration 0 of the shade rendering — with the final drawing obtained by applying the designed shade rendering via physical feedback.

3.6.3. Comparing the two types of visual feedback

When comparing the two drawings in Fig. 17, the perceptual differences between the drawing using only computational feedback and the one based on physical (camera-based) feedback show important differences, where the latter method gives richer shading with wider tonal ranges. More examples of using computational feedback are shown in Fig. 18, and two additional portraits using physical feedback are shown in Fig. 19.

4. On the characteristics of the drawings

From the experience of exhibiting Paul's production to a wide audience we have noticed that the produced portraits are perceived, considered and appreciated as drawings. A series of Paul drawings are recognised as drawn by the same author as they

[11] This is the same contrast curve as mentioned in step 2 of the drawing cycle.

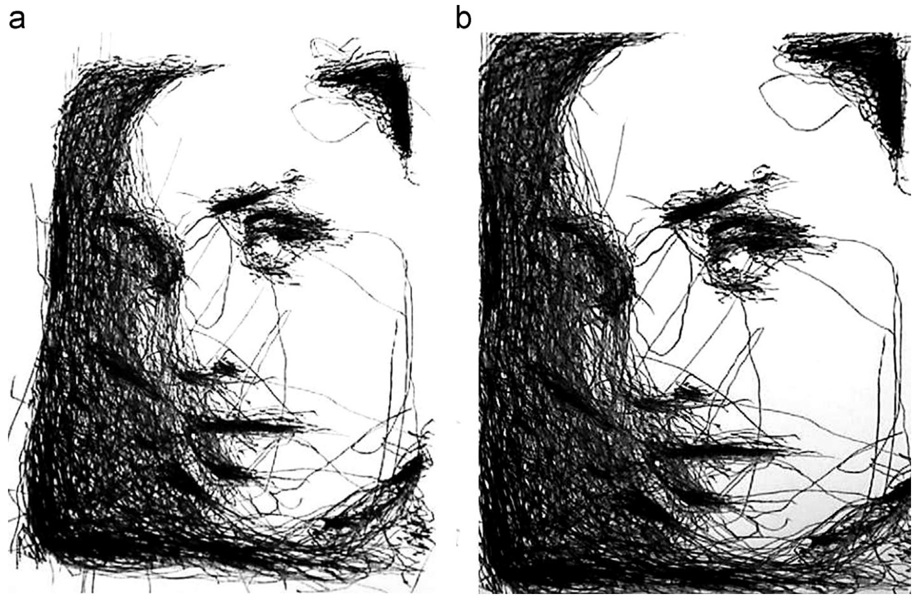

Fig. 13. Undistort and homography processes: (a) view as captured by the camera (cropped); (b) view after the undistort and homography transforms have been applied.

display an autographic style. Still, there is rather little doubt about their non-human authorship, especially when observing at close range details of Paul's outputs. However, contrary to other computational systems that produce drawings from photographs such as AIkon-I [22], drawings produced by Paul do not display the same serial uniformity of treatment (Figs. 11 and 19). Paul can be evaluated from two different perspectives: (i) as a human–robot interactive installation, and (ii) as a system that generates drawings. In this section we focus on the latter, by evaluating Paul's production.

4.1. *Drawing surface as an object*

An artwork is an object that has to be perceived as rare, collectible and of high quality. The paper used for Paul's drawings has been chosen with great care to add to the feeling of quality, and to bring the appearance closer to a traditional drawing. To distance the general appearance of the drawings from a printed, computer-generated artefact, the paper that Paul draws on measures 28 cm $\times$ 38 cm, a proportion very dissimilar to the ISO 216 (A5, A4, A*n*), proportions so widespread in the contemporary visual environment. The size is significantly larger than A4, adding to the feeling of quality and uniqueness. In publishing, magazines or books of larger sizes departing from the norm, are associated with quality. The paper chosen is of "conservation quality", meaning that its composition facilitates its preservation over a long period: it is made of 100% rag (cotton fibres) and weighs 300 g per sheet. It has a NOT (not hot pressed) surface, *i.e.* a slightly relief paper texture, off white in colour. These qualities influence how the drawing is perceived by the public at large, connoisseurs (curators, critics, collectors) and visual artists, associating the drawing's appearance with that of a traditional drawing of quality.

4.2. *General layout*

The placement and scale of the drawing on the sheet of paper influences the readability and the aesthetic effect of the drawing on the observer.[12] This notion is based on the artist's numerous years of experience, a subject we have not been able to nor tried to make explicit and simulate (*i.e.* we consider it part of the "Experience" node in Fig. 2, that will require future work).

4.3. *The lighting and pose*

Each time Paul is exhibited in a new location, a calibration process is necessary to adapt the system to the ambient light. In effect, the calibration stage consists of creating a contrast curve that is then applied to the grayscale image of the sitter prior to any further processing. Furthermore, for each sitter the light directed onto the face can be reviewed by the person that manipulates Paul, and if judged necessary the light position and direction are adjusted. This stage is of importance as lighting has an impact on the character and aesthetic qualities of a drawing.

4.4. *Artist–Robot collaboration*

Patrick Tresset has spent more than 13 years of his adult life practicing drawing and painting at a professional level. As such Patrick, like any artist, has developed an expertise in the evaluation of drawings. During Paul's development Patrick has evaluated its drawings with the same level of standards as if they were his own. During any artistic practice, the evaluation of the work is of great importance. The artistic practice has two stages: (i) the development of an individual style, achieved through research and practice which usually take years, and (ii) the application of this technique to produce artworks. Hence, we can say that Patrick has 'collaborated' with Paul on the former phase of the artistic practice as the succession of processes implemented in Paul are closely inspired by the strategies deployed by Patrick when drawing by hand. Patrick evaluates Paul's output with the same stringent standards until the drawings are considered of sufficient quality to be considered artworks (stage (i)). During exhibitions and for commissions Paul executes autonomously the execution phase of the artistic practice (stage (ii)).

4.5. *A naive drawer*

Because it lacks memory of previous work and has no knowledge of face structures, Paul can be considered a *naive* drawer (*i.e.* it lacks elaborate schemata and does not acquire experience,

[12] The face drawing is in a rectangle of 14 $\times$ 19 cm centered horizontally 11 cm from bottom.

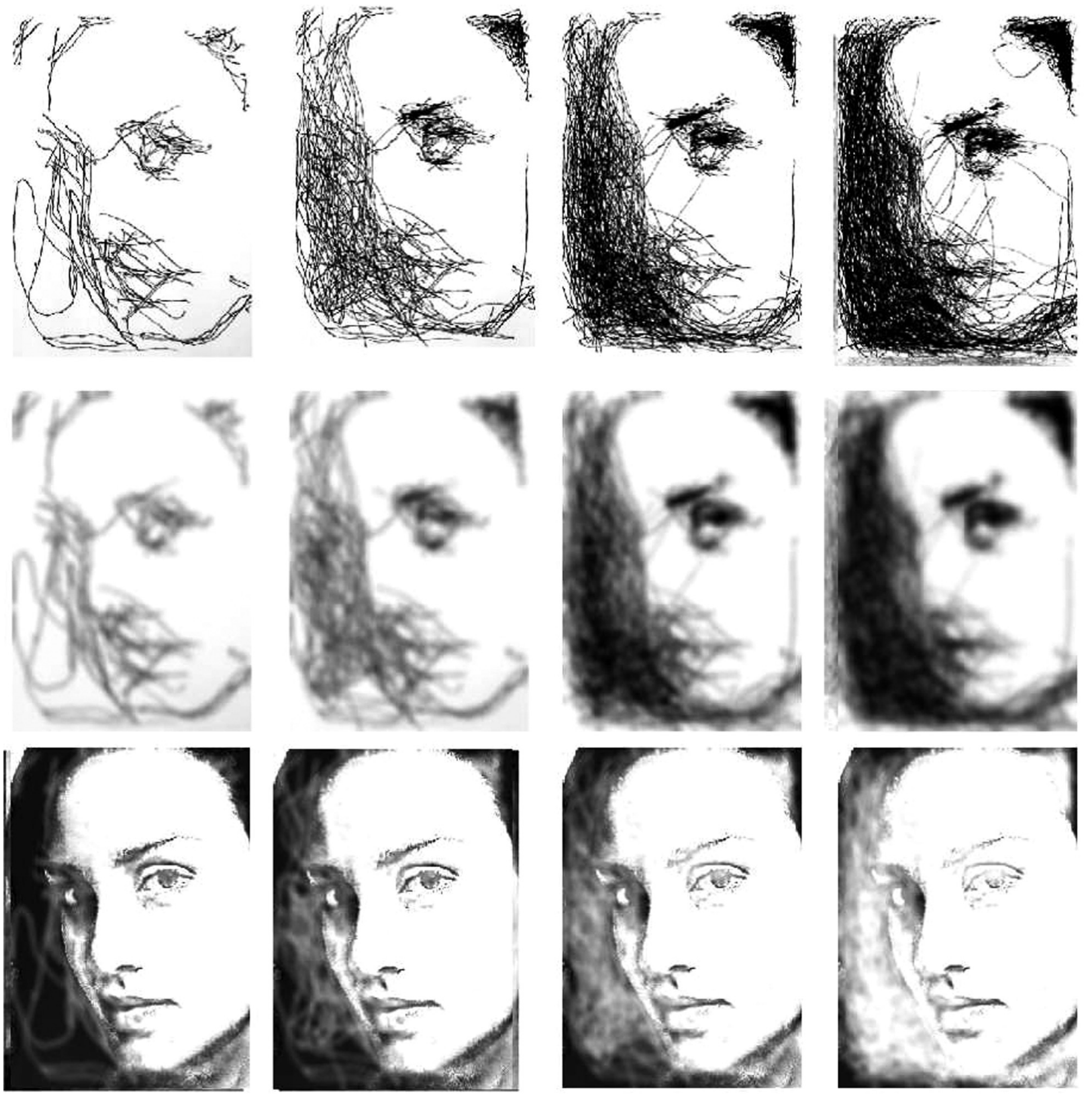

Fig. 14. Intermediate results for the physical visual feedback loop: From the left to right, iterations 2, 8, 32 and 62, for each column, row top to bottom indicate: drawing view undistorted, filtered view, and (evaluation) error.

Fig. 2). As such, however, its drawings are not "contaminated" by the knowledge of a subject, what Van Sommers calls the "conceptual bias" [46]. Studies have demonstrated this is one of the factors that causes misrepresentation amongst drawers [47], *e.g.* leading them to draw circles where an ellipse is more truthful (such as the border of a glass seen at an angle).

4.6. The depiction of salient features

When Paul draws salient lines, their paths are extracted from the responses of Gabor kernels [36] applied to an image of the subject at varying scales. Such kernels are known to be good models of simple cells in the early visual cortex (V1) [44]. In computational models of bottom-up visual attention such as in Itti et al.'s work [49], Gabor kernels are used to build one of the saliency maps based on orientation contrast. Areas that display high disparities become salient regions. It has been observed that during the perception of natural scenes, salient areas attract the focus of attention. Interestingly, in the context of a visuo-motor activity such as drawing a line, Coen-Cagli et al. have observed through eye-tracking experiments that fixations can be predicted from an orientation saliency map [50]. Collomosse and Hall's work on painterly rendering effectively used image saliency as a factor to modulate levels of detail rendered in NPR effects [51]. We can speculate that the use of what are in effect saliency orientation maps to plan the movements that Paul will perform in the first part of the drawing cycle contributes to the portrait being interpreted in a manner similar to how a hand-made drawing would be perceived.

4.7. The influence of decisions based on visual feedback

Although there is no use of visual feedback for high-level decisions in Paul's current (naive) behaviour, there is use of

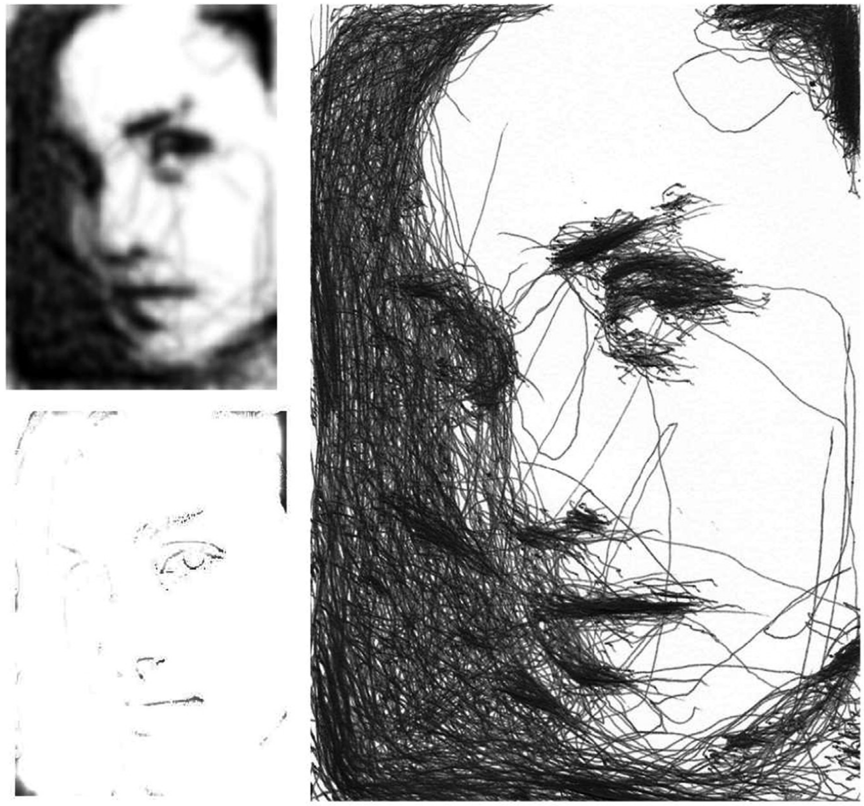

Fig. 15. Final iteration for the physical visual feedback loop: filtered view (top-left), error (bottom-left) and drawing (right).

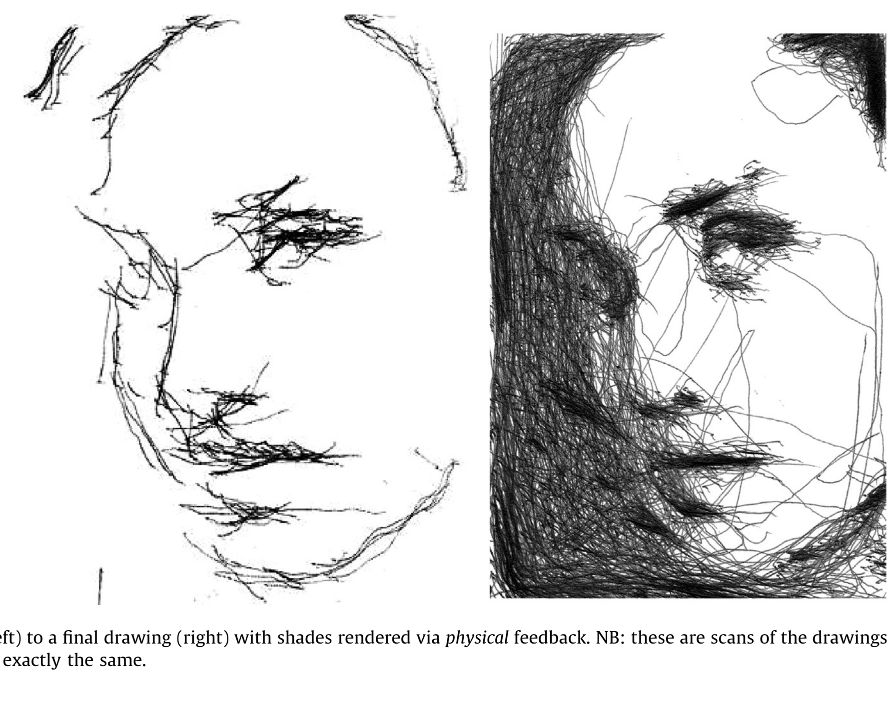

Fig. 16. From salient lines (left) to a final drawing (right) with shades rendered via *physical* feedback. NB: these are scans of the drawings done on paper by Paul, and the scaling and cropping are not exactly the same.

feedback at lower levels for motor control and during the shade rendering process. The use of feedback (computational or physical) to constrain and evaluate the random exploration at play during the shading process seems to be sufficient to produce patterns that are perceived as not entirely due to chance. As such they can appear to be the result of an intentional process.

4.8. Paul's physicality

Artists, art critics, psychologists and other specialists often cite the recoverability of the genesis of a drawing as one of the most important factors contributing to the appeal and affective effects such an artefact can have on an observer [52,53]. Based on the recent discovery of the neural mirror system, it has been

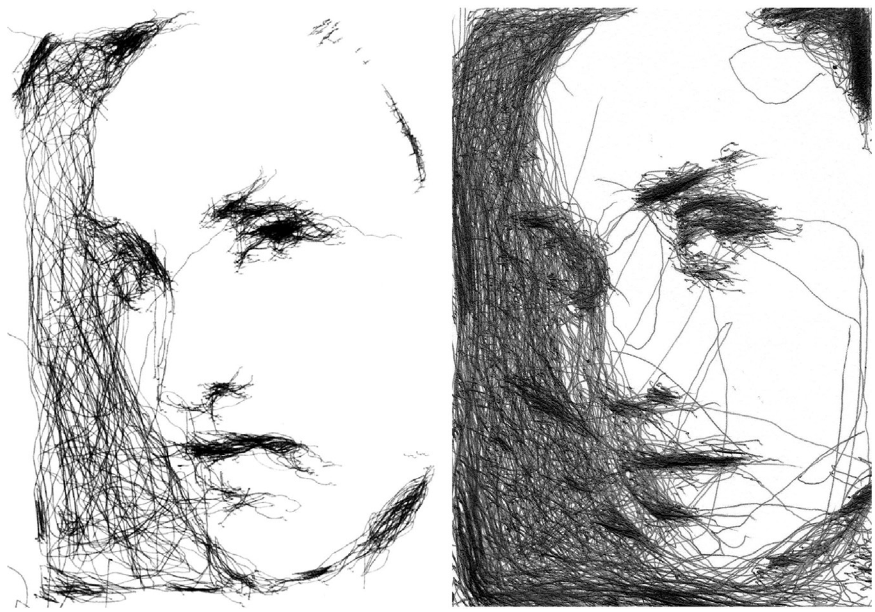

Fig. 17. Comparison of the result of using (left) computational versus (right) physical feedback in shade rendering, where in both cases, the starting point is a similar initial drawing of salient lines (cropped views).

Fig. 18. Another four signed portraits by Paul, using computational feedback for shade rendering in addition to initial salient lines (cropped views), 2011.

suggested that some of the actions deployed to create a drawing are mirrored in parts of the observer's neural system, and this could amplify their emotional response [54]. In a drawing each line is a direct record of the artist's hand motion and the drawing itself a record of a specific sequence of actions performed by the drawer. In effect, a drawing is a precise physical record of the artist's intentions [55]. Evidence that the lines that are part of a drawing by the robot are the results of movements can be found in the resulting irregularities [56]. Drawn lines have qualities that are a direct consequence of the characteristics of the gestures that traced them. The single hand-drawn mark or stroke generally displays cues from which humans can infer the direction of the movement that created it. Babcock and Freyd have observed that human subjects spontaneously copy lines in the same directions as they were drawn [57]. Interestingly they have also observed that when subjects were explicitly asked to identify the direction in which the lines to be copied were drawn, the success rate was lower than when spontaneously copying, which strongly suggests that there is an association between the perception of the line and motor planning and execution. The mark also displays cues about the velocity at which the line was drawn, as well as pressure. Although the lines and marks drawn by Paul the robot are not identical to artefacts a human would produce, they have characteristics that are the result of a pen moving on paper, driven by an articulated arm. Furthermore the layering of successive lines and patterns during the drawing cycle adds to the drawing being perceived as the consequence of a sequence of movements [58].

4.9. Shading patterns

Although the shade patterns generated by Paul are reminiscent of the style of Tresset, Giacometti, Dryden Goodwin, and other artists, they are not the most commonly used. Often when a naive observer or a non-drawer sees drawings produced by Paul at close range they interpret the patterns used for shading literally, describing them as “the robot going mad”, “cobweb”, “hairs” and so on. When such drawings are observed at a distance by

Fig. 19. Two more examples of portraits by Paul, using physical feedback for shade rendering in addition to initial salient lines, 2012 (cropped views).

drawing practitioners or connoisseurs such an interpretation is not reported.

Our most recent experimental implementation of the shading behaviour controlled by physical feedback produces drawings that, even when seen at close range by "un-trained" observers, are not perceived as being odd. This is likely due to the produced shading patterns, which are of higher densities with smoother tonal transitions.

5. Conclusion

This communication presented Paul the robot as a naive drawer of face portraits. Although the individual algorithms driving Paul are relatively simple and not particularly novel, the way in which they are combined is of interest as the drawings Paul produces are considered by professionals as being of artistic value, which is unusual for computer-generated figurative portraits. With this work we are further suggesting that the field of NPR in computer graphics should not only consider more carefully modeling and simulating the artistic creative and generative processes via purely software implementations [20], but should also seriously consider the embodiment of such systems. Designing and building robot artists can serve a number of interesting and additional purposes, including: (i) providing new insights into the processes to put in place and their sequencing and interactions in greater similitude to human artists who have to consider when and how to interact with an artwork with their body, such as when evaluating the history and quality of the layout of lines already used in shaded areas; (ii) impacting the type of algorithms to consider and permitting to design specific mechanisms — such as various forms of feedback — which otherwise would likely remain unrecognised; (iii) orienting the form of perceptual mechanisms put in place, *e.g.* actions linked to schemata, such as drawing gestures in relation to camera/eye gazing; and (iv) enforcing proper line drawing actions where features (such as blob samples) are explicitly covered by strokes. This approach can also permit the field of computer graphics to have greater impact on the field of robotics itself.

We have also introduced a comprehensive range of factors that may explain why Paul's drawings are perceived as being of interest to a specialised audience as well as to the public at large. Although no further major developments are planned for Paul itself, a number of public exhibitions are scheduled for the coming two years (2013–2014). The next important milestone will be the implementation of another embodied system, currently under study. This new robot, a descendant of Paul, will take into consideration more sophisticated visual feedback such as processing, as a human artist would do, the patterns resulting from the salient lines extraction process presented in this paper. This new artistic robot will also be influenced by levels of knowledge of the human face, *e.g.* proportions, hence moving away from the naive drawer that Paul is. We expect the drawing capacities of this next generation of robots to be significantly different from Paul's.

Conceptually, in the context of the AIkon-II project, a longer-term goal of our research is to obtain a better understanding of the human artist in action, how she perceives and re-interprets the subject of the artistic depiction, here a human face. We have taken the view that embodied systems offer us a more likely route to reach such a goal, while purely software-based systems as studied in the context of most computer graphics (and vision) research have in our view failed to break new grounds in that direction. In any case, having more sophisticated embodied bio-mimetic graphical systems should allow us as a community of researchers to draw the line between what is reasonable and effective via software only, such as pursued in the usual NPR context, and what is beneficial or even simply different with embodied robotic systems.

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Appendix A. Exhibits

The various contexts in which Paul has been exhibited include: (i) *traditional visual art* at the Tenderpixel Gallery (June 2011), the exhibit of the first Thinking Through Drawing Symposium (NY, Oct 2011), The London Art Fair (Jan 2012), Gallery H+ (Lyon, Sept. to Dec 2012), the Merge Festival (London, Oct 2012); (ii) *digital art* at ISEA (Istanbul, Aug 2011), the Kinetica Art Fair (London, Feb 2012); (iii) the *general public* at the Victoria and Albert Museum in London, at PopTech! (Camden, Maine, Oct 2011), as part of the Intuition and Ingenuity group exhibition in celebration of the Alan Turing Centenary (UK, 2012) and at other smaller venues.

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