Recovering 3D Structure From Images and Inertial Sensors

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ABSTRACT

Advanced sensor systems, exploring high integrity and multiple sensorial modalities, have been significantly increasing the capabilities of autonomous vehicles and enlarging the application potential of vision systems. The article describes the cooperation between two relevant sensors - image and inertial sensors. Inertial sensors coupled to the active vision system can provide valuable information, as happens with the vestibular system in human and other animals. Visual and inertial sensing are two sensory modalities that can be explored to give robust solutions on image segmentation and recovering of three-dimensional structure from images.

This article presents our recent results on the use and integration of those two modalities. In a first example we use the inertial information to infer one of the intrinsic parameters of the visual sensor - the focal length, after defining the horizontal plane (horizon). The second example relies on segmentation of images, by labelling the vertical structures of image scene. In a third example we use the integration of inertial and visual information to detect the regions in the scene that we can drive a vehicle: in our case the levelled ground plane.

1 INTRODUCTION

Advanced sensor systems, exploring high integrity and multiple sensorial modalities, have been significantly increasing the capabilities of autonomous vehicles and enlarging potential applications of vision systems. The article describes the cooperation between two relevant sensors - image and inertial sensors. Visual and inertial sensing are two sensory modalities that can be explored to give robust solutions on image segmentation and recovering of three-dimensional structure from images. The cooperation between these two sensory modalities may be useful for the elaboration of high-level representations such as multi-modality three-dimensional maps, detection of specific three-dimensional structures in the images such as levelled ground or vertical structures.

Inertial sensors are a class of sensors useful for internal sensing and they are not dependent on external references. In human and other animals the ear vestibular system gives inertial information essential for navigation, orientation or equilibrium of the body. In humans this sensorial system is crucial for several visual tasks and head stabilisation. This is a sensorial modality, which co-operates with other sensorial systems and gives essential information for everyday tasks. One example of co-operation is between the vestibular sensorial system and the visual system. It is well known that, in humans, the information provided by the vestibular system is used during the execution of navigational and visual movements, as described by Carpenter [6]. However the inertial information is also important for head-stabilisation behaviours, including the control of body posture and equilibrium.

The inertial information can also be useful on applications with autonomous systems and artificial vision. In the case of active vision systems, the inertial information gives a second modality of sensing that gives useful information for image stabilisation, control of pursuit movements, or ego-motion determination when the active vision system is used with a mobile platform. This kind of sensorial information is also crucial for the development of tasks with artificial autonomous systems where the notion of horizontal or vertical is important - see [7] for example.

A vision system with inertial sensors obtains a partial estimation of *self-motion* or *absolute orientation* from inertial information. The gravity, the rigid body acceleration, and the angular instantaneous velocity can be measured from these sensors, the instantaneous velocity, the angular position and linear translation of the vision system can also be obtained. The cooperation between these quantities with visual information can be useful to estimate the instantaneous visual motion, to segment images (for example between moving objects and background), estimation of vision system orientation with respect to the horizontal plane or to recover depth maps based on the estimation self-motion.

This article presents our recent results on the use and integration of those two modalities. In a first example we use the inertial information to infer one of the intrinsic parameters of the visual sensor - the focal length and after defining the horizontal plane (*horizon*). The second example relies on segmentation of images, by labelling the vertical structures of image scene. In a third example we use the integration of inertial and visual information to detect the regions in the scene that we can drive a vehicle: in our case the levelled ground plane. The solution is based on information about the scene that could be obtained during a process of the visual fixation, complemented by the information provided by inertial sensors.

2 NOTATION AND BACKGROUND

A projection point $\vec{p} = (u, v)$ in each camera image is related with a 3D point $\vec{P} = (X, Y, Z)$ by the perspective relations

$$u = f\frac{X}{Z} \qquad v = f\frac{Y}{Z} \tag{1}$$

where u and v are the pixel co-ordinates with origin at the image centre, f is the focal length, and $\vec{P}$ is expressed in the camera referential.

Suppose an image unit sphere where every point $\vec{X}$ in the world is projected. The projection is

$$\vec{X} \mapsto \vec{q} = \frac{\vec{X}}{\|\vec{X}\|} \tag{2}$$

Note that $\vec{q} = (q_1, q_2, q_3)$ is a unit vector and the projection is not defined for $\vec{X} = 0$. Projection onto the unit sphere is related to projection onto a plane by

$$(u, v) = \left(\frac{fq_1}{q_3}, \frac{fq_2}{q_3}\right) \tag{3}$$

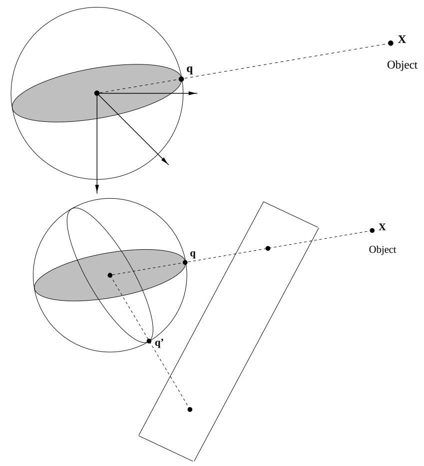

Figure 1: Projection onto Unit Sphere.

Given f, the projection to a sphere can be computed from the projection to a plane and conversely.

The angle between two unit vectors $\vec{q}$ and $\vec{q'}$ is

$$\cos\theta = \vec{q}^T\vec{q'} \tag{4}$$

and two vectors $\vec{q}$ and $\vec{q'}$ are *conjugate* to each other if

$$\vec{q}^T\vec{q'} = 0 \tag{5}$$

2.1 Vanishing Line

A line l on the image plane whose equation is $Au + Bv + C = 0$ has homogeneous coordinates $\vec{l} = (A, B, C/f)$. This line is the intersection of the image plane $Z = f$ with a plane $AX + BY + CZ/f = 0$, passing through the viewpoint. The vector $(A, B, C/f)$ is perpendicular to this plane and l has a direction

$$\vec{n} = \pm\frac{\vec{l}}{\|\vec{l}\|} \tag{6}$$

A planar surface with a unit normal vector, not parallel to the image plane has, when projected, a *vanishing line* $\pm\vec{n}$ [17] - see figure 2. Since the *vanishing line* is determined alone by the orientation of the planar surface, then the projections of planar surfaces parallel in the scene define a common *vanishing line*. A *vanishing line* is a set of all *vanishing points*.

If unit vectors $\vec{q}$ and $\vec{q'}$ are *conjugate* and (u, v) and (u, v) are the image points of these points then

$$\vec{q}^T\vec{q'} = uu' + vv' + f^2 = 0 \tag{7}$$

and the focal length f could be estimated.

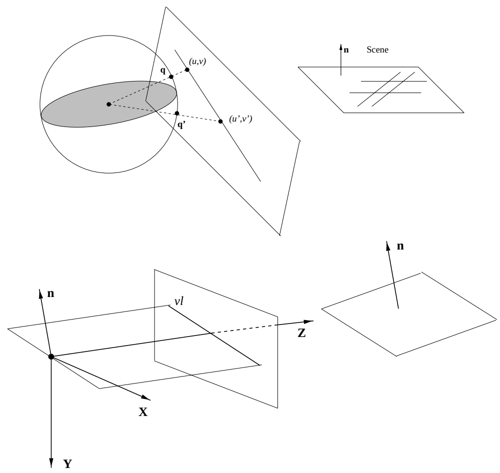

Figure 2: Vanishing line.

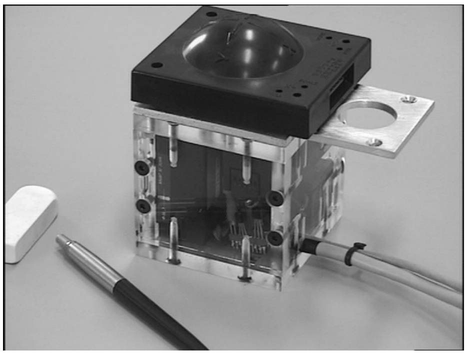

Figure 3: The inertial system prototype.

3 THE PROTOTYPE

To study the integration of the inertial information with vision systems, including active vision systems, we decided to develop an inertial system prototype composed of low-cost inertial sensors. Their mechanical mounting and the necessary electronics for processing were also designed. The sensors used in the prototype system include a three-axial accelerometer, three gyroscopes and a dual-axis inclinometer. They were mounted on an acrylic cube as seen in figure 3.

The three-axial accelerometer chosen for the system, while minimising eventual alignment problems, did not add much to the equivalent cost of three separate single-axis sensors. The device used was Summit Instruments' 34103A three-axial capacitive accelerometer. In order to keep track of rotation on the x-, y- and z-axis three gyroscopes were used. The piezoelectric vibrating prism gyroscope Gyrostar ENV-011D built by Murata was chosen. To measure tilt about the x and y-axis a dual axis AccuStar electronic inclinometer, built by Lucas Sensing Systems, was used - see [12] for details. These type of inertial systems, known as *strap-down systems*, have been developed and used for navigation in mobile robotics and terrestrial vehicles. To estimate position with inertial systems, a double integration of the accelerometer data is performed. For now we are only extracting the camera's attitude from the accelerometer data. This is done by keeping track of the gravity vector $\vec{g}$. The accelerometer sensor by Summit Instruments comes with a factory calibration table, providing sensitivity, offset and alignment data. The complete system is initially calibrated by placing it on a flat, levelled tabletop and estimating the offsets. The actual implementation estimates the camera's attitude when it was still. The gyros are intended to track all rotations so that the attitude can be known when accelerations other than gravity are present [18].

3.1 The Vision System

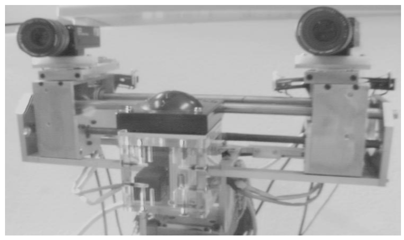

Figure 4: The active vision system.

The inertial system prototype can be mounted onto one single camera or onto an active vision system such as in the figure 4. For the active vision system the whole system runs on a 120MHz Pentium PC running a public domain unix operating system, the FreeBSD [15]. An Advantech PCL818HD data acquisition card was included to handle the inertial sensor acquisition. A Matrox Meteor framegrabber was used to capture the images from the Sony XC-999 cameras. The FreeBSD driver for the Meteor was reprogrammed to handle the Advantech board and enable sensor data acquisition synchronous with the captured frames. This system, whilst not enabling top performances, is very flexible and reconfigurable.

3.2 The Mobile System

To study the integration of the inertial information in artificial autonomous systems we developed a prototype based on the same inertial system but with a different computational architecture. Figure 5 shows the architecture of the system that supervises the active vision, moving platform and inertial system. The inertial system is continuously monitored by the onboard host computer.

To handle the inertial data acquisition the Advantech card was also used. This card has input filters, A/D and D/A converters and EISA bus interface, where the card is connected along with a framegrabber for image acquisition and processing.

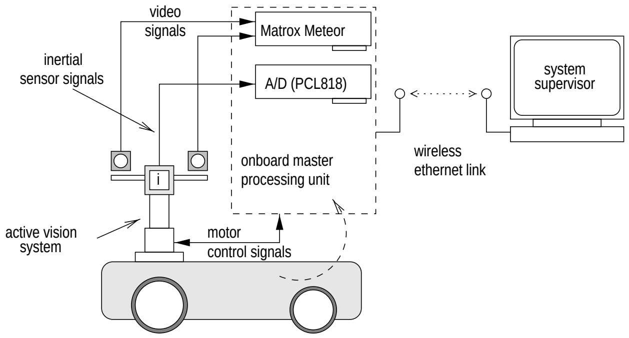

Figure 5: System Architecture. The inertial system processing board uses the Master processing unit as host computer.

4 RESULTS

4.1 First Example: The *horizon* line and focal length estimation

The measurements $\vec{a}$ taken by the tri-axial accelerometer include the sensed gravity vector $\vec{g}$ summed with the body's acceleration $\vec{a}_b$ as stated in (8). Figure 6 shows the relevant coordinate systems.

$$\vec{a} = \vec{g} + \vec{a}_b = \begin{bmatrix} g_x \\ g_y \\ g_z \end{bmatrix} + \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} \tag{8}$$

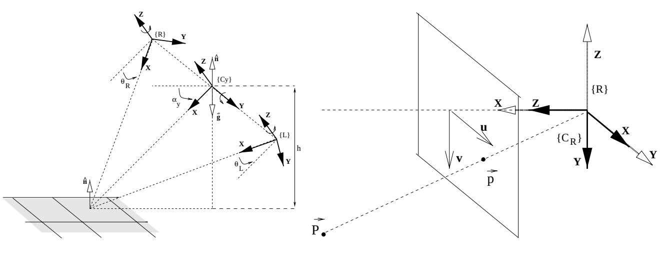

Figure 6: World, cube and image coordinates.

Assuming that camera is still, then $\vec{a}_b = 0$ and the measured acceleration $\vec{a} = \vec{g}$ gives de gravity vector in the camera's referential. This vector is normal to the world ground plane, and we can write out the equation of a level ground plane as

$$X g_x + Y g_y + Z g_z = h \tag{9}$$

in the camera's referential, where h is the cameras height from ground level.

If we intercept this plane (with $h = 0$) with the image plane we get the horizon line.

Using two *conjugate* points in the horizon line (two *vanishing* points), the the focal distance f can be estimated from (7). These two vanishing points can be determined from the intersection of two orthogonal lines belonging to the ground plane.

So making $Z = f$, where f is the focal distance of the camera, and performing the perspective transformation to image coordinates, the horizon line is given by:

$$\begin{gathered} \frac{u}{s_u f} f g_x + \frac{v}{s_v f} f g_y + f g_z = 0 \\ v = -\frac{s_v}{s_u}\frac{g_x}{g_y} u - f s_v \frac{g_z}{g_y} \end{gathered} \tag{10}$$

where u and v are the image horizontal and vertical coordinates, and s_u and s_v the respective scaling factors. Assuming that image acquisition maintains square pixel ratio we have $s_u = s_v = s$. This can be reasonably accomplished if some care is taken in programming the framegrabber (see [16]). Equation (10) can then be re-written as

$$v = -\frac{g_x}{g_y} u - f s \frac{g_z}{g_y} \tag{11}$$

If the camera is levelled with ground this simply becomes $v = 0$ since $g_x = 0$, $g_y = 1$, $g_z = 0$. In fact, with the square pixel assumption, the scaling factor only becomes relevant when the camera is pitched, i.e. $g_z \neq 0$.

In an image the horizon can be found by having two distinct vanishing points [17]. With a suitable calibration target (e.g. a square with well defined edges) the unknown scaling factor can be determined. In fact only one vanishing point is enough since the slope of the line is already known.

The quality of the estimation of sf depends on the noise level in the accelerometer data. In our test the artificial horizon would jog up and down a couple of pixels when the accelerometer's data is not properly filtered. Nevertheless it provides a reasonable estimate for a completely un-calibrated camera. In the experimental tests a calibration target was used, as

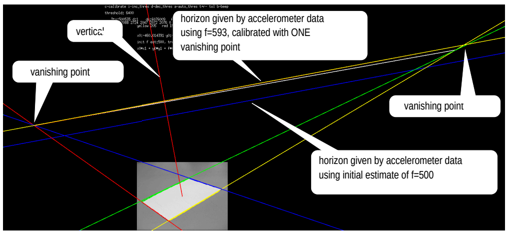

Figure 7: Image vanishing points and the estimated horizon.

can be seen in figure 7. The camera pose was chosen so as to have a good perspective distortion. Having estimated this scaling factor, as above or from some other calibration procedure, the artificial horizon can be correctly traced onto the image.

4.2 Second Example: Detection vertical lines

If the camera only rotates on world x and z, the vertical features will remain parallel in the image since they remain frontal and parallel to the image plane. The slope of these vertical lines is also given from the accelerometer data as explained above. These lines are given by the following equation:

$$u = \frac{g_x}{g_y} v + u_0 \tag{12}$$

given in image coordinates. This is just a general line perpendicular to the horizon line given in (11).

In order to detect vertical lines we extract the edges in the image using a Sobel filter. The filter was applied to estimate the gradient magnitude at each pixel. By choosing an appropriate threshold for the gradient, the potential edge lines can be identified. The square of the gradient was used in our application to allow faster integer computation. To obtain the vertical edges only we could compare the pixel gradient with the expected gradient for the vertical lines given by the slope of the line in (12). But this only leads to erroneous results since the pixel gradient provides a very local information and is affected by the pixel quantization. In order to extract the vertical lines in the image a simplified Hough transform was used. The Hough transform was only applied for the relevant slope, i.e. an histogram of the image edge points was performed along the vertical given by the accelerometers. So each edge point (u, v) contributed to the histogram at position

$$histogram\_position = (u, v).(g_x, -g_y) \tag{13}$$

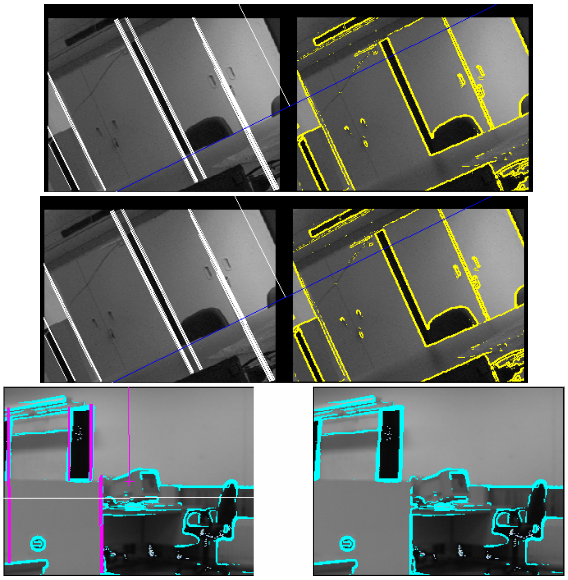

Figure 8: Detected vertical lines.

This histogram, besides counting the number of points, also kept track of the endpoints so that the line could be correctly traced when mapped back to the image. By thresholding this histogram the relevant vertical edges in the image can be found.

Figure 8 shows the results obtained with the system running at 10 frames per second. The left image shows the vertical edges extracted. The right image shows the initial edge points resulting from thresholding the estimated gradient given by the Sobel filter. On the left image, the identified vertical edges are shown.

4.3 Third Example: Identifying the ground plane

The inertial data is used to keep track of the gravity vector, allowing the identification of the vertical in the images and segment the levelled ground plane in the images. By performing visual fixation of a ground plane point, and knowing the 3D vector normal to level ground, we can determine the ground plane. The image can therefore be segmented, and the ground plane along which a mobile robot or vehicle can move, identified. For on-the-fly visualisation of the segmented images and the detected ground points a VRML viewer is used.

4.3.1 System Geometry

For the ground plane segmentation we used the inertial unit placed at the middle of an active vision system

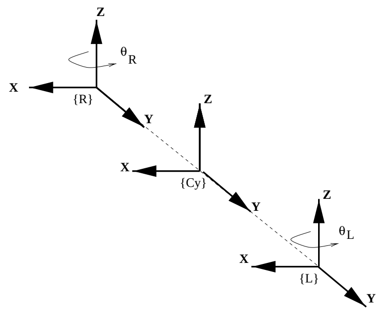

Figure 9: System Geometry.

in the point $\{C_y\}$, as seen in figure 9. The head co-ordinate frame referential, or Cyclop $\{C_y\}$is defined as having the origin at the centre of the baseline between the two stereo cameras.

A projection point $\vec{p} = (u, v)$ in each camera image is related with a 3D point $\vec{P} = (X, Y, Z)$ by the perspective relations. If we know $\vec{P} = (X, Y, Z)$, finding the projection (u, v) is trivial. The reverse problem involves matching points between the left and right images. Establishing this correspondence will give us enough equations to determine the 3D co-ordinates, if a few vision system parameters are known. However if visual fixation is used, the geometry is simplified and the reconstruction of the 3D fixated point is simplified, as can be seen in figure 10. Notice that the visual fixation can be achieved by controlling the active vision system and the geometry generated by the process allows a fast and robust 3D reconstruction of the fixation point - see [9] and [10] for details.

4.3.2 Inclinometer gives the ground plane orientation

The inclinometer data can be used to determine the orientation of the ground plane. In order to locate this plane in space at least one point belonging to the ground plane must be known. When the vehicle is stationary or subject to constant speed the inclinometer gives the direction of $\vec{g}$ relative to the Cyclop referential $\{C_y\}$. Assuming the ground is levelled, and with α_x and α_y being the sensed angles along the x and y-axis, the normal to the ground plane will be

$$\begin{aligned}\hat{n} &= -\frac{\vec{g}}{\|\vec{g}\|} \\ &= \frac{1}{\sqrt{1-\sin^2\alpha_x-\sin^2\alpha_y}}\begin{bmatrix} -\cos\alpha_x\sin\alpha_y \\ \cos\alpha_y\sin\alpha_x \\ \cos\alpha_y\cos\alpha_x \end{bmatrix}\end{aligned} \tag{14}$$

given in the Cyclop frame of reference. Using this inertial information the equation for the ground plane will be given by

$$\hat{n}.\vec{P} + h = 0 \tag{15}$$

where $\vec{P}$ is a point in the plane and h is the distance from the origin of $\{C_y\}$ down to the ground plane.

4.3.3 Estimation of ground plane

To obtain a point belonging to the ground plane it is necessary to establish a mechanism to achieve visual fixation. This mechanism was developed in our laboratory and is described in [9] and [10]. If the active vision system fixates in a point that belongs to the ground plane, the ground plane could be determined in the Cyclop referential $\{C_y\}$ using the inclinometer data. Hence, any other correspondent point in the image can be identified as belonging or not to the ground plane.

If the fixation point is identified as belonging to the ground plane, the value of h in (15), can be determined. As seen in figure 10 (where only α_y is non null to keep the diagram simple) h will be given by

$$h = -\hat{n}.\vec{P}_f \tag{16}$$

When visual fixation is obtained for a ground point and assuming symmetric vergence (i.e. $\theta = \theta_R = -\theta_L$) from (16) and (14) we have

$$h = -\hat{n}.\vec{P}_f = \frac{b\sin\alpha_y\cos\theta}{2\sin\theta} \tag{17}$$

as can easily be seen in figure 10 (where α_x is null, but (17) still holds for any α_x).

This value of h will be used to determine if other points in the image belong or not to the level plane passing the image centre point (i.e. fixation point).

4.3.4 Image Segmentation of the ground plane

An algorithm for the image segmentation of the ground plane can now be presented, based on the solution of (16).

To express a world point $\vec{P}$, given in the camera referential, on the Cyclop referential $\{C_y\}$ we have

$$^{C_y}\vec{P} = ^{C_y}T_{C_R}.^{C_R}\vec{P} = ^{C_y}T_R.^{R}T_{C_R}.^{C_R}\vec{P} \tag{18}$$

$$^{C_y}\vec{P} = ^{C_y}T_{C_L}.^{C_L}\vec{P} = ^{C_y}T_L.^{L}T_{C_L}.^{C_L}\vec{P} \tag{19}$$

From (19) the point expressed in the Cyclop referential is given by

$$^{C_y}\vec{P} = ^{C_y} T_{C_R} . ^{C_R}\vec{P}\,(u_R, v_R, \lambda_R) \tag{20}$$

where λ_R represents an unknown value (depending on depth from camera). Substituting (20) in (15), λ_R can be determined and hence $\vec{g}$ is completely known in the Cyclop referential. Expressing $\vec{P}$ in the $\{C_L\}$ referential by

$$^{C_L}\vec{P} = ^{C_L} T_{C_y} . ^{C_y}\vec{P} = \left(^{C_y}T_{C_R}\right)^{-1} . ^{C_y}\vec{P} \tag{21}$$

the correspondent point of interest (u_L, v_L) generated by the projection of P in the left image is given by

$$u_L = S_u f \frac{X}{Z} \qquad v_L = S_v f \frac{Y}{Z} \tag{22}$$

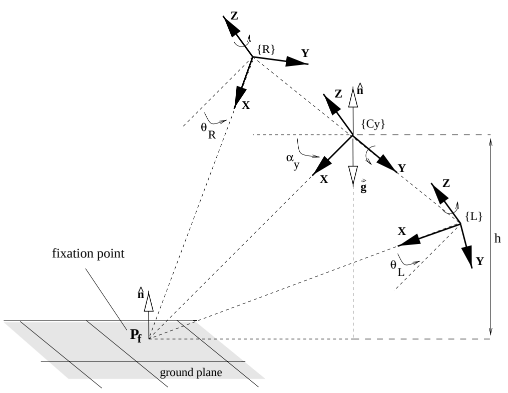

Figure 10: Ground plane point fixated. The point $\vec{P}_f$ in the ground plane is visualised by the active vision system. The geometry of this visualisation corresponds to a state, named visual fixation.

Starting with a point of interest in one of the images, say the right image (u_R, v_R), is possible to establish the *collineation* to left image (u_L, v_L). Taking λ_R out of (17) and (20) and substituting in (21) and (22) we get a set of equations that give this *collineation* for a given a set of stereo images.

Defining a point in the right image, the correspondent point and its neighbourhood in the left image can then be tested for a match with the original point of interest in the right image. If there is a match, the point belongs to the ground plane. If there is no match the point must be something other than the floor, possibly an obstacle.

Figure 11 show the matched ground plane points of interest. Grahams Algorithm [14] was used for computation of the convex polygon envolving the set of points. Adjusting a convex polygon to the set of points can lead to erroneous ground patch segmentation.

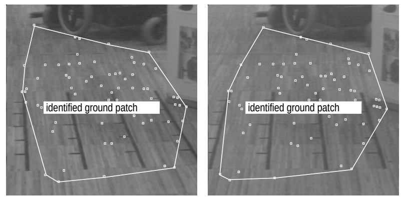

Figure 11: Identified ground patch.

4.3.5 Viewing with VRML

For visualisation of the detected ground points a VRML (Virtual Reality Modelling Language) world is generated [1]. VRML has become the standard for describing 3D scenes on the Internet. A web browser with the appropriate plug-in lets the user see the images from the robots viewpoint, or change the viewpoint and "fly" around the 3D world viewed by the vision system. The identified ground plane patch can be mapped onto the 3D scene, as seen in figure 12.

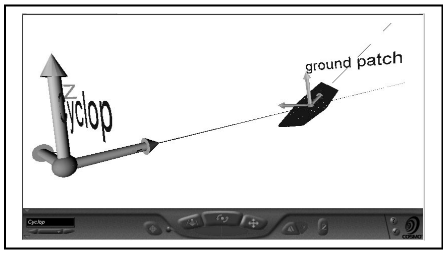

Figure 12: VRML view of ground patch with detected points.

5 CONCLUSIONS

The integration of inertial sensors with vision opens a new field for the development of applications based or related with inertial information. In this article we described three examples of integration of inertial information and vision.

Inertial sensors coupled to mobile vision systems enable some interesting results. The accelerometer data can provide an artificial horizon, short of a vertical scale factor. This factor can be estimated using image vanishing points or other camera calibration methods. The accelerometer data also gives information about the vertical in the image. Knowing this vertical is very important to extract relevant image features. In the tests the vertical edges in the image were correctly identified. Future work involves refining the final stage of the vertical edge extraction to include edge tracking and hysteresis. We also intend to use the inertial data in more dynamic ways, by using the gyro data as well as the accelerometers.

Information about the ground plane extracted from the inertial sensors is used to identify the floor plane using the simulation of visual fixation with an active vision system. By fixating the visual system on a point in the ground plane, the 3D position of the plane in space is obtained. Any other correspondent point in the stereo image can be identified as belonging or not to the ground plane. Segmentation of the image is therefore accomplished. Some ground detection results were presented. For on-the-fly visualisation of the detected points a VRML world is generated which can be viewed in any web browser with the appropriate plug-in. VRML opens many other possibilities such as tele-operation or path-planning environments.

Acknowledgements

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