Tgi3D® SU PhotoScan

CalibrationTool

User's Guide

(revision 1.1.11)

**Tgi3D SU PhotoScan v1.23
and higher**

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1. Introduction

Tgi3D® CT (Tgi3D® SU PhotoScan Calibration Tool) calibrates cameras from photographs. The user marks matching points in multiple photographs, then the program computes camera parameters and 3D location of the given points. You can export the calibration to other tools or you can perform distance measurements on the model.

The following section explains a typical workflow in a camera calibration project, then Sections 3. to 7. provides brief information on user interface related issues on each of the processing steps in the workflow. Finally Section 8. provides useful guidelines on picture taking, point matching and many other issues to obtain accurate camera calibration results.

Note for Mac OS X Users: Effective usage of the Tgi3D SU PhotoScan Calibration Tool requires a 3-button mouse. If you do not have a 3-button mouse, we recommend you to use a program like KeyRemap4MacBook (http://pqrs.org/macosx/keyremap4macbook/) to generate scroll wheel, middle-button and right-button click events (e.g. command-control-cursormove, command-click and control-click respectively).

2. Workflow

In order to create 3D models of objects first you need to take the pictures of the object from different angles. Intuitively, your pictures should cover the whole object so that it does not have any parts that is not seen by any photograph and you also want to make sure that each photograph has a good overlap with at least one of the remaining photographs. Also note that using too many photographs with very large overlaps is only a burden on you and the program. See Section 8. for a more detailed description of picture taking guidelines. After taking the pictures and loading them in Tgi3D® CT, you need to identify matching points. Matching points are the projections of a single point in 3D space on the photographs. See Section 8. for extensive guidelines on matching points.

Note: Avoid editing/cropping/non-linear-filtering photographs in image (or photo) editors. Tgi3D® CT works best with untouched original data coming from digital cameras. Try using JPEG format with full EXIF (Exchangeable Image File Format) info which is almost universal default format for digital cameras.

Creating 3D Models from photographs with Tgi3D® CT involves the following processing steps:

1. Create a new project or open an existing project See Section 3. for a brief information on Tgi3D® CT projects.

2. Load several photographs of the object taken from different angles into the project as needed. See Section 4. for the details of this processing step.

3. Identify matching points on different photographs. At this step you can also assign 3D locations to the points as additional information. The calibration tool is able to utilize this additional information to improve accuracy. See Section 5. for the details of this processing step.

4. In the calibration step, camera parameters are determined. These parameters will include positions and viewing angles of the camera(s) for each photograph (external parameters) as well as focal length and radial distortion (internal parameters). The calibration tool reads camera make and model and focal length from JPEG files. Calibration tool has a camera database comprising thousands of cameras. The EXIF information from the JPEG files and the database are used to form an initial approximation to the camera parameters. If the camera does not exist in the default database it is possible to add the camera to a local database, also if the photograph does not include any camera information you can still enter the initial parameters manually. In calibration step you can optionally include accuracy computation. See Section 6. for the details of this processing step.

   Note: Steps 3 and 4 can be repeated after reviewing the calibration report and log files.

5. Reconstruct the model. Reconstructed model can be viewed in 3D. You can also measure 3D distances between points. If in the calibration step you have included accuracy computation the measurements will be reported along with the associated uncertainties. At this step you have to enter an external measurement between a pair of points for the program to scale the world correctly. You may also want to define a world coordinate system by providing the origin and a number of axes vectors. The reconstructed model (and the calibration information if destination format is SketchUp) can also be exported to various formats. See Section 7. for the details of this processing step.

3. Tgi3D® CT Projects

Tgi3D® CT works with a collection of files grouped into a "project" that are placed in a user selected folder on the computer file management system. The project is identified with a file having ".prj" extension in the same folder. Loss of any of the of the files, except the "outputs" sub-folder, in the project folder results in loss of information or even the loss of the whole project due to file integrity violation. The "outputs" folder on the other hand holds temporary outputs can be deleted to save space in case of porting the project to another location.

3.1. Creating a new project

To create a new project:

1. Issue a *New Project* command in one of the following ways:

   ○ Select *File > New project...* from Menu bar

   ○ Click *New Project* button from the File toolbar.

   ○ Use keyboard shortcut Ctrl+N (command-N on Mac)

2. Select a folder (or create a new folder) to create the project using the "Browse For Folder" dialog box and click "OK".

The name of the project is assigned to be the same as the name of the selected folder.

If you already have another project open and the project has unsaved work before this action, you will be prompted to save the current project, continue without saving, or cancel the operation.

When a new project is opened, the name of the new project appears on the title bar and the project is empty at the beginning, i.e. there are no images listed in the project window and the drawing and viewing area is empty.

Note: If you have another project in the folder that is selected as a placeholder for the new project, that project is opened instead of a new project.

3.2. Opening an existing project

To open an existing project:

1. Issue an *Open Project* command in one of the following ways:

   ○ Select *File > Open project...* from Menu bar

   ○ Click *Open Project* button from the File toolbar.

   ○ Use keyboard shortcut Ctrl+O (command-O on Mac)

2. Browse for and select the existing project file with extension ".prj" from the "Open Project" pop-up dialog and click "OK".

If you already have another project open and the project has unsaved work before this action, you will be prompted to save the current project, continue without saving, or cancel the operation.

When an existing project is opened, the name of the project appears on the title bar, the list of images included in the project will be listed in the Project Window and the drawing and viewing area will show the images.

3.3. Saving the project

To save the your work on the currently selected image click *File > Save* from the Menu bar.

To save a project:

1. Issue a *Save All* command in one of the following ways:
   - Select *File > Save All...* from the Menu bar
   - Click the *Save All* button on the File toolbar.

4. Loading and Navigating Through Photographs

When the project is created it is empty and does not contain any images, First thing to do after creating the project, is adding photographs to the project. In order to mark matching points, one should be able to navigate easily between and inside the loaded photographs to access any location on any photograph at a desired zoom level. Precision in marking points demands high zoom ratios, while avoiding erroneous matches require lower zoom ratios where whole the scene is visible. Various window layouts and zooming and navigation techniques including a magnifier window are available in Tgi3D® CT, to enable fast and error-free marking of points.

4.1. Loading Photographs

For accuracy and completeness the photographs need to cover the object(s) of interest from various viewing angles so that all the parts of the object(s) are visible in the photographs. Another important requirement in taking pictures is each photograph to have a good overlap with at least one of the remaining photographs. Note that using too many photographs with very large overlaps satisfies the two requirements above; but it will only become a burden on you and the program; therefore you would want to minimize the number of photographs. For many cases of simple objects, two views are sufficient to calibrate and reconstruct but for better results use at least three photographs. See Section 8. for a more detailed description of picture taking guidelines.

Note: Avoid editing/cropping/non-linear-filtering photographs in image (or photo) editors. Tgi3D® CT works best with untouched original data coming from digital cameras. Try using JPEG format with full EXIF (Exchangeable Image File Format) info which is almost universal default format for digital cameras.

To load photographs into the project:

1. Issue an A*dd Images* command in one of the following ways:

   ○ Select *File > Add Images...* from Menu bar

   ○ Click the *Add Images* button from the File toolbar.

   ○ Use keyboard shortcut Ctrl + I (command-I on Mac)

2. Browse for and select the images you want to load into the project, then click "Open".

4.2. Workspace layout and photograph navigation

The workspace layout of Tgi3D® CT has two main components, namely *Project Window, and Drawing and viewing area* as shown in Figure 1-(a) and (b). The *project window* contains panes displaying the images in the project, camera calibration results and the cameras used in the 3D reconstruction. It also contains a sub-window called *Image Info* that provides information about the selected image together with the internal parameters of the corresponding camera. The *Drawing and Viewing Area* displays selected image and allows editing of calibration poins*. The *project* and *image info* windows can be shown and hidden using the corresponding items in the *View* menu as shown in Figure 1-(b) and (c).

You can navigate through the photographs in various modes determined by the items found under the *View* and *Window* menu. The following are the ways to navigate between the photographs:

• **The project window:** The project window, which can be shown or hidden by the *View > Project Window* command displays a list of all the photographs in the project and allows you to navigate by clicking on the photograph names in the list as shown in Figure 1-(a) and (b).

• **The selection tabs:** The selection tabs above the *Drawing and Viewing Area* is another mechanism for photograph navigation as shown in Figure 1-(a). Simply click on the tab to switch to activate the corresponding view.

• **Window menu:** Finally, the N*ext*, *Previous* and *Last Active* commands under the *Window* menu provides universal methods to navigate through the photographs.
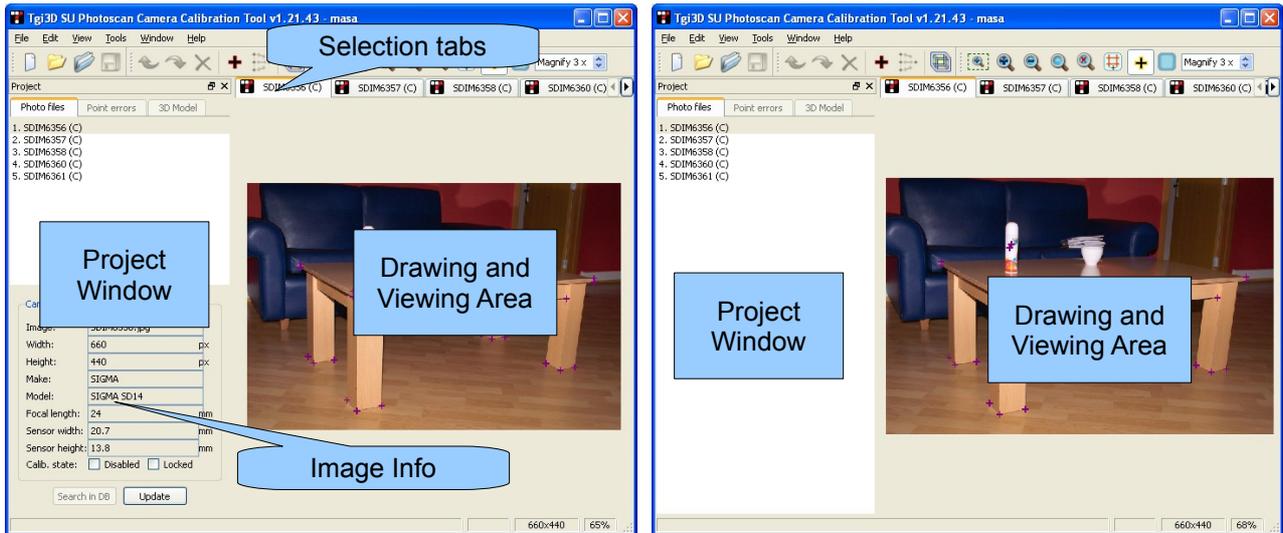
(a)

(b)
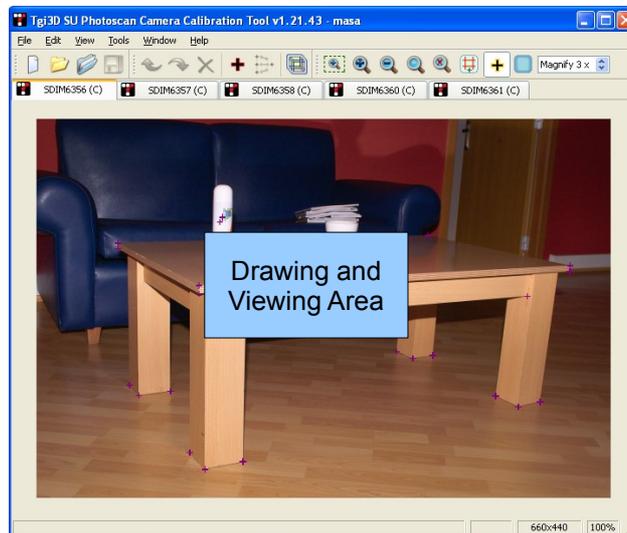
(c)

Figure 1: Different layouts of the main window

4.3. Navigating Inside a Photograph

Various types of zooming operations and panning form the ways of navigation inside a photograph:

a) Zooming in and out

To zoom in and out of the image:

1. Do one of the following:

    ○ Select the *View > Zoom In* or *View > Zoom Out* from the menus.

    ○ Click the *Zoom In* or *Zoom Out* buttons on the Zoom toolbar.

- Use mouse wheel when *View > Enable Mouse Wheel Zoom* option is checked.
- Use "+" or "-" keys on the keyboard

b) Zooming to fit the window frame

To fit the image to the window frame:

1. Do one of the following:
   - Select *View > Fit to Screen* from the menus.
   - Click the *Fit to Screen* button on the Zoom toolbar.
   - Use "." (the dot) key on the keyboard.

c) Zooming to selected area

To zoom to a selected rectangular area in the image:

1. To activate the zoom box drawing option, do one of the following:
   - Select *View > Zoom Box* on the menus.
   - Click the *Zoom Box* button on the Zoom toolbar.
   - Press and hold the 'Z' key on the keyboard.
2. Draw a zoom box (a rectangular area) by clicking and dragging left mouse button.

d) Zooming to view selected items

To zoom all the images to selected points:

1. Do one of the following:
   - Select *View > Zoom to Selections* from the menus.
   - Click the *Zoom to Selections* button on the Zoom toolbar.

e) Zooming to image dimensions

To zoom to the actual dimensions of the image:

1. Do one of the following:
   - Select *View > Normal Size* on the menus.
   - Click the *Normal Size* button on the Zoom toolbar.
   - Use the "0" (zero) key on the keyboard.

f) Panning

To pan the image

1. Do one of the following:
   - Drag the image using the middle mouse button
   - Use the scroll bars on the right hand side and the bottom of the image view
   - Use mouse wheel for vertical scrolling when *View->Enable Mouse Wheel Zoom* option is unchecked

g) Magnifying

To enable the magnifier, press and hold the 'Shift' key on the keyboard. A magnifier window will appear around the window. The default magnifier level can be set via the magnification ratio spin box on the toolbar. The navigation inside the magnifier is similar. You can

    i.   Zoom in and out using the mouse wheel,

    ii.   Pan by dragging the image with the middle mouse button, and

    iii.   Navigate over the original image by dragging the window with the right mouse button.

5. Identifying Matching Points

Matching points are the projections of a single point in 3D space on the photographs. For example, the corner of a table can be a calibration point in 3D and its matching points are the 2D locations of the corner on the photographs that sees the corner as shown in Figure 2. Precision of marking the matching points affects the accuracy of calibration but it is impossible to localize the matching points with infinite precision. Choosing matching points as sharp features, and having a wide distribution over the photographs and in 3D space are basic guidelines to be followed in identifying matching points. See Section 8. for more extensive guidelines.
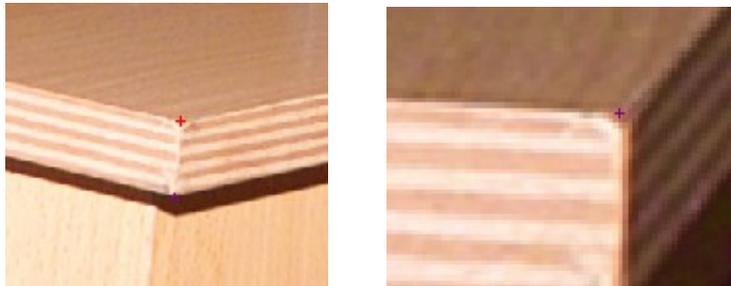
Figure 2: The corner of a table on two different photographs

Especially in complex scenes such as buildings or smooth textured surfaces the matching point identification can be error prone if a systematic approach is not followed. The most common source of error is false matches arising due to to periodicity or wide angle differences between the views.

There are two common approaches to matching point identification on the images. In the first one a new feature in the scene or an existing feature is chosen and its projections are found and marked on the images that see it. The second one serves to increase calibration accuracy and can only be used on calibrated cameras and reconstructed features in the scene. The projections of reconstructed points are observed and marked if necessary.

5.1. Matching Point Identification without 3D reconstruction

Here is a simple systematic approach for matching point identification from scratch:

1. Do one of the following:

    •   Choose a feature in the scene such as the corner of a table or some type of a point like texture on a surface or a special marker inserted in the scene.

    •   Choose an existing point using calibration point list sub-window, which will select its matching points marked previously.

2. Choose a moderate zoom level so that you can see a large enough portion of the scene to differentiate the chosen feature from similar ones.

3. Visit each photograph and by enabling the calibration point placement (or pressing and holding the 'C' key while clicking) mark the feature using the magnifier if it is visible and not already marked. The magnifier helps sub-pixel accurate localization of the feature. The calibration point created will remain selected after it is created.

4. Match the points by clicking the Match points button in the toolbar or use the right mouse button on one of the selected points. Matching clears all the selections

5. Go to step 1 for another feature.

If you have a large number of photographs, do the identification and calibration incrementally. First mark and calibrate a subset of cameras and points, then add more points or photographs after making sure that the calibration of the subset is satisfactory. If you have too many photographs and pictures it may be very difficult to find even a single false match.

5.2. Matching Point Identification using the 3D Model

The accuracy of camera calibration increases with the number of matching points. It is usually difficult to mark many matching points from sratch without any guides; peridocity or the complexity of the scene can make it difficult to find the projections of a feature on all the images from scratch. Mostly small number of points are identified to obtain a roughly calibrated system, then the number of matching points are increased using the projections of the reconstructed points over the images.

(a)   (b)

(c)   (d)
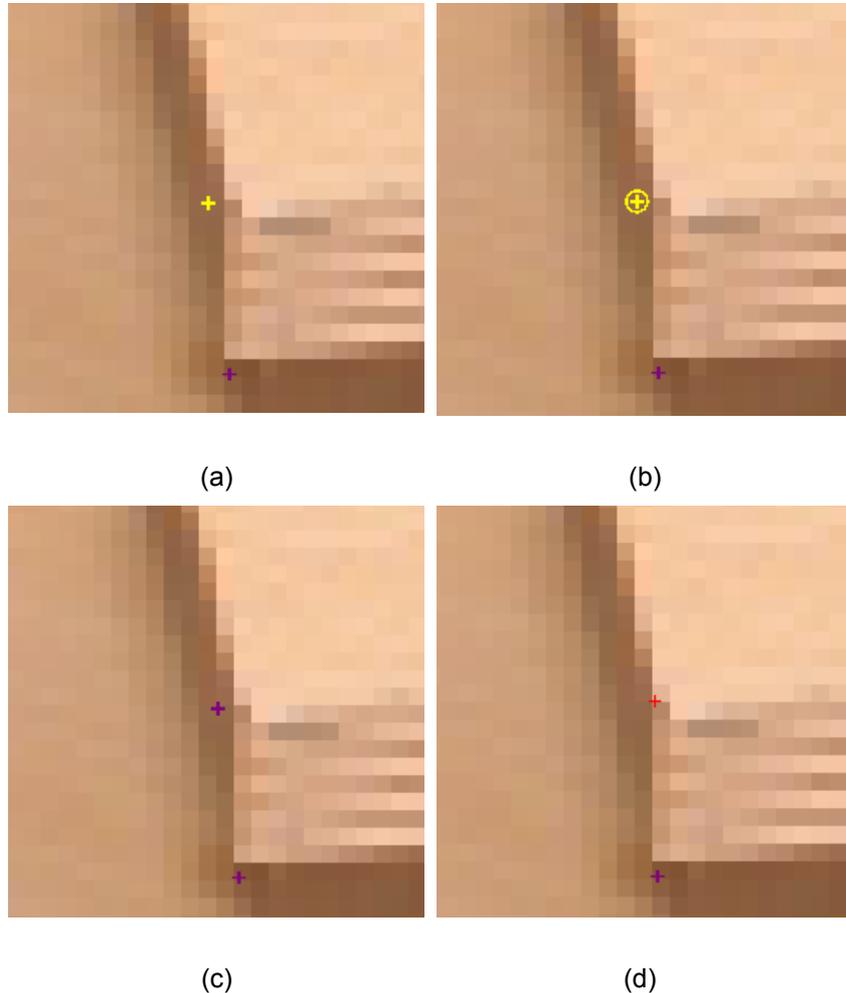
Figure 3: The states of identifying the the projections of reconstructed calibration points.

In this method

1. Calibrate the system and build the 3D model.

2. Use the *Show point projections* command on the toolbar or in the **View** menu. If a point in the model does not have a matching point on an input image then its projection is displayed with a yellow marker as shown in Figure 3-(a).

3. Click on the yellow marker to select all the matching points of the correspoinding 3D point on the rest of the images. The marker will change shape as shown in Figure 3-(b)

4. Check the existing projections to understand the corresponding feature in the scene. The feature shown in Figure 3 is the upper corner of a table.

5. Click on the marker again to add the point as the matching point for the feature. The point will be displayed with a regular selected marker as shown in Figure 3-(d).

6. Drag the point to the center of the corresponding feature as shown in Figure 3-(d) .

7. Apply the steps 3 to 6 especially on the projections that are far away from their true locations on the image.

5.3. Calibration Point Handling

The purpose of this interface is to place matching points accurately. The basic operations of calibration point creation are:

a) Inserting a point

1. Do one of the following:

   ○ Select *Edit > Calibration Point* on the menus.

   ○ Click the *Calibration point* button on the *Edit* toolbar.

   ○ Press and hold the 'C' key on the keyboard.

2. Activate the magnifier by pressing shift key on the keyboard, if the zoom level is not high enough for the desired precision.

3. Position the cursor (focus at the desired location) and click (left) mouse button.

b) Selecting a point

   • Position the cursor over the point and click the left mouse button.

When a point is inserted it is also selected. Selected point appears highlighted in red. The names of the images that have selected points in them will be marked with (p+) in the Project window and on the tabs above the *Drawing and Viewing Area*.

c) Zooming to a selected point

   • Select *View > Zoom to Selections* menu item or click *Zoom to Selections* button on the Zoom toolbar.

d) Unselecting a point

   • Press and release the 'Esc' key on the keyboard.

e) Moving a point

   • Position the cursor over the point, press and hold the left mouse button, move the cursor, and release at the desired new position.

f) Magnifying around the cursor

   • Press and hold the 'Shift' key. The default magnification ratio of the magnifier can be set form magnify spin-box in the zoom toolbar. See Section 4.3. g) for more details on using the magnifier.

5.4. Projection Handling

After the 3D model is built, S*how point projections* command on the toolbar or in the *View* menu can be used to display their projections.. If a point in the model does not have a matching point on an input image then its projection is displayed with a yellow marker as shown in Figure 3-(a). It is possible to select and convert projections to matching points.

a) Selecting a projection

   • Click on the point or use the point navigator (see Section   5.6.) to select a projection and its corresponding matching points on the rest of the images. The marker will turn into a yellow plus sign

inside a circle when the projection is selected as shown in Figure 3-(b)

b) Converting a projection to a matching point

- Just click on the selected projection to convert it to a regular matching point.

5.5. Matching/unmatching Points

Tgi3D® CT uses collections of points on each photograph that are matched to a single corresponding 3D point on the object. To match points:

1. Select the points in each photograph which correspond to the same 3D point.
2. Click the right mouse button in a photograph with a selected entity. This will launch the *Match/unmatch Selected Points* dialog box.
3. Click "Match" button on the *Match/unmatch Selected Points* dialog box.

You can perform the match in incremental steps, that is, if you match a new entity to another entity that already has a group, it is equivalent to matching all the entities in that group at once.

5.6. Navigating Through Calibration Points

Pressing and holding 'M' key in a photograph will bring an overlayed sub-window (on the top left corner of the image window) displaying 3D calibration point ids (i.e. Matched Point IDs) or projections as shown in Figure 4. These numbers are selectable with a left-mouse-click. If you select a point or match group or a projection, all corresponding points in the photographs in that group will be selected .

It is also possible the track the matching information using the projection points on the photographs. The following keys display matching information on demand:

- Pressing and holding 'Q' key will display matched point ids of all points as shown in Figure 4
- Pressing and holding 'B' key will display the matched point id of the selected points only.

You can de-select all the points in all photographs by clicking on the "Deselect" button in the *Match/unmatch Selected Points* dialog box.

If you have made a false point match or inaccurate point matches, then you would want to destroy (or unmatch) a matching group. To unmatch a group of points, you may follow the steps below

1. Press 'Q' key and read the id of the point with false match
2. Press 'M' key and left click on that group id
3. Right mouse click on one of the selected points
4. Click "Unmatch" button on the *Match/unmatch Selected Points* dialog box.

5.7. Assigning 3D Coordinates to a Point

If there are no points selected on other photographs, right mouse clicking on a point brings up the 3D coordinate dialog box from which you can enter, change or remove 3D coordinate values. You should enter coordinates separated by space or ',' (comma). You can select the coordinate units from the pull-down units menu inside the 3D coordinate dialog box. The defaults units are millimeters.
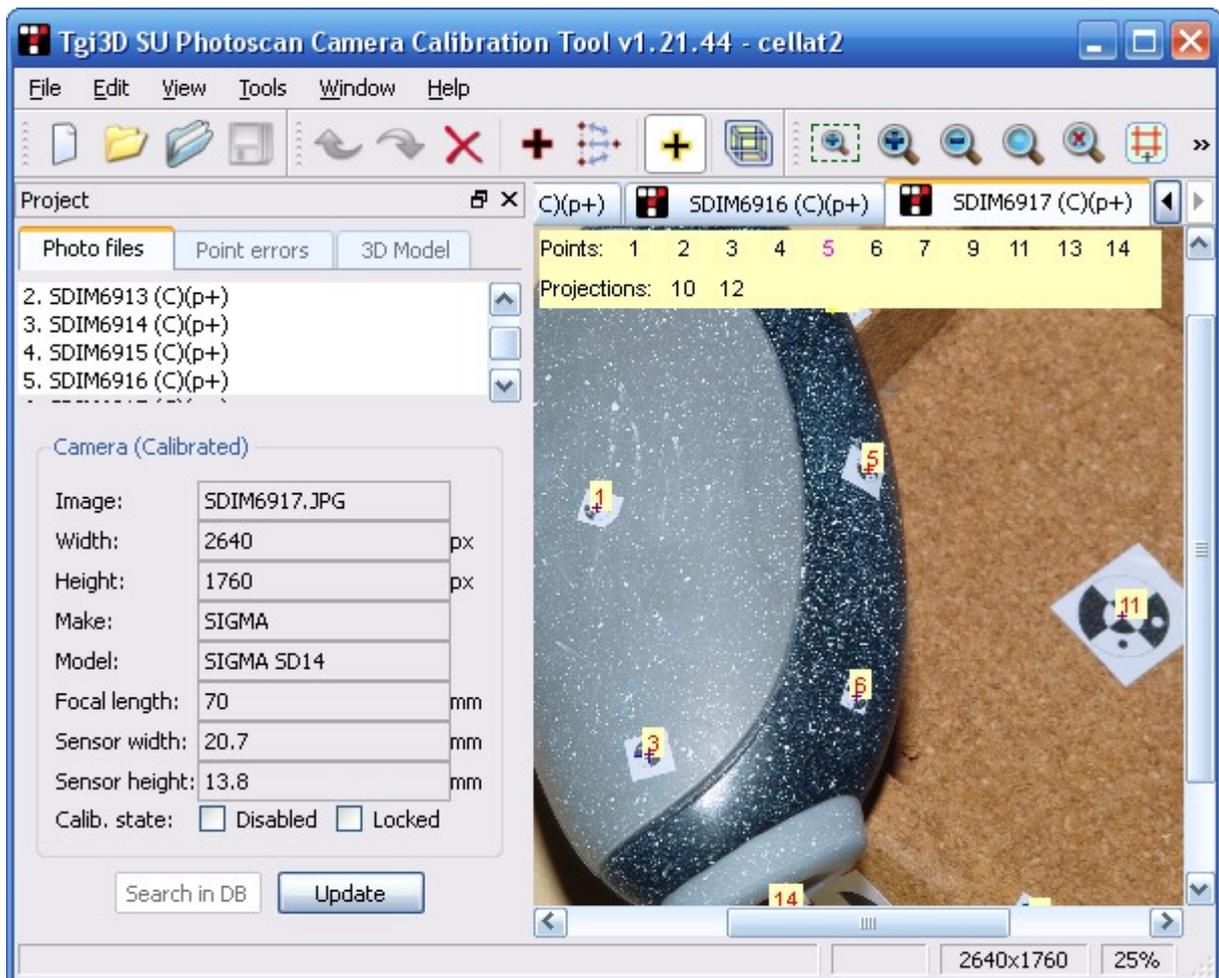
Figure 4: Navigating calibration points.

6. Camera Calibration

The camera calibration requires **at least 8 points** to be matched for at least one pair of images. If the focal length and/or sensor size information can not be extracted from the EXIF info or the internal/external camera database for the photographs, then you may also edit the camera parameters of the images before starting calibration.

To edit camera information of a photograph:

1. Select "Photo files" tab in the project window.

2. Double clicking on the photograph name pop's up the *Image Info* dialog box.

3. If the EXIF info is present in the photograph and the camera exists in the central database you cannot change any of the camera related information.

4. If EXIF info was successfully read but camera does not exist in the camera database, then you can enter sensor size parameters in the *Camera Info* dialog box. Typically you can find that information through the internet or from the manual of the camera.

5. If no EXIF info was found in the photograph, you can select a camera from the database and enter a compatible focal length or just enter focal length for a 35mm camera..If you do not set anything it is going to be assumed to be a 35mm camera with a default focal length set by the system.

To calibrate the cameras, use the *Tools > Camera Calibration* command for the *Camera Calibration Settings* dialog box to show up. There are two basic settings associated with camera calibration:

- If you want accuracy level computation to be performed, select the "Create Calibration Uncertainty (or Accuracy) Information' option in the dialog box. With this option being on, the measurements are reported with uncertainty using 95% (i.e. $2\cdots$) confidence interval. Checking this option will slow down the camera calibration process slightly.

- By default the calibration computations use the previous calibration as the starting point, in rare cases, this may create a convergence problem. You can initialize the calibration completely by selecting the "Ignore Previous Calibration" option in the dialog.

After setting the desired options, click "Run" button to calibrate the cameras. When the calibration is completed a report containing internal camera parameters, projection errors and estimated user error is generated, you can review the report by clicking "View Report" button. The project window and the selection tabs will indicate the calibrated cameras with a (C) symbol following the name of the photograph.

Tgi3D® CT calibration tool is able to perform calibration even with gross user errors, if there are sufficient correctly entered points. When calibration process is completed, point calibration errors are reported as a list inside the *Project Window* under the "Point errors" tab (where largest errors reported first). You can navigate through and fix calibration points by clicking on the errors in the report list. High error rates indicate bad calibration mostly due to inaccurate point matches or false matches.

By default calibration tool generates the most accurate calibration, for normal cases. In case of failures, you can also choose to follow the advanced camera calibration process, to get a finer control of the calibration engine. The best way to cope with calibration failures is to provide more and more calibration points visible on as many cameras as possible. Advanced calibration is the very last resort meant for users with basic technical knowledge on image formation and parameter estimation process. In general, if the correct focal length information on the cameras are available and there are plenty of calibration points you should not need to use the advanced calibration.

Advanced calibration allows you

1. To supply a default focal length for the cameras with unknown focal lengths

2. To decrease the complexity of the camera model by fixing the focal length and/or radial distortion to constant values. A camera model with fewer degrees of freedom helps the system converge with fewer number of points.

3. Adjust the number of iterations through the 'recalibration count' field. 10 should be enough for most cases. If you increase this number much above 100, then the calibration will take a long time.

4. You can also save the current calibration to the local camera database. This way if the same camera

same focal length combination is encountered the calibration starts from a much better approximation.

7. Reconstruction / Exporting

Once the camera calibration is complete, it is possible to reconstruct and view the calibration points. You can launch the 3D model viewer by doing one of these::

- Select *Tools > Build 3D model*

- Click *Build 3D model* button from the *Edit* toolbar

- Use keyboard shortcut Ctrl+R (command-R on Mac)

The 3D viewer window is activated and identified by the label 'model'. The calibration points are shown in 3D overlaid with the photographs. If you left click on a 3D point its projections are automatically selected and marked as such.

The 3D viewer lets enter an external measurement between a pair of points for the program to scale the world correctly and define a world coordinate system by providing the origin and a number of axes vectors. Right double clicking on a points sets it as the origin of the world coordinate system. Consecutive right clicks on two different points pops up a context menu that

- displays the distance measurement and allows editing it using the distance measurement dialog box,

- set the vector between the points parallel to an axis in the world coordinates. If the two points are the same it can be set as the origin of the world coordinate system.

- delete the measurement or the axis constraint or the origin associated with the point(s)

The 3D viewer can show the model from an arbitrary viewing angle. It also contains fixed views for each calibrated camera. By clicking on the tabs above the model window or the entries 3D model page of project window, you can navigate to camera views corresponding to that photograph.

It is also possible to judge the quality of calibration from the reported 3D distance uncertainties. High uncertainties indicate semi-stable calibrations. Increasing the number of calibration points and/or the number of photographs can help increase the quality of calibration and reconstruction.

Finally, when you are satisfied with the quality of reconstruction and calibration you can export it to other formats by either selecting *Tools > Export* or using keyboard shortcut Ctrl-E (command-E on Mac), which will launch the Export Dialog box. The export dialog box allows you to select an output format and the image resolution level for exporting the camera parameters, images and the reconstruction of points used in calibration.

Note: Currently calibrated camera parameters and images are exported only for SketchUp by creating "Photo Match" pages which lets the user draw easily over the images. In other formats only the reconstructed points are exported.

8. Guidelines for Improving Accuracy

Tgi3D® CT correctly reports the level of achieved accuracy, and the user can confidently decide on usability of the measurement results. Using Tgi3D® CT and today's digital cameras, it is possible to obtain average modeling errors as small as 0.1 pixels and relative distance errors less than 1 part in 10000. For most applications this level of accuracy is not needed. Still, if you want to get the most out of the calibration tool and the photographs, a few simple guidelines that you can follow are listed below.

- **Accuracy expectation:** Your relative uncertainty in a distance measurement will roughly be positional uncertainty (in pixels) divided by the largest number of pixels covered in a photograph by that distance. Therefore your distance measurement accuracy will increase by the photographs pixel size and decrease by blur. You will find that doubling the image size by interpolation will in general give you no accuracy gain. Depending on the image quality reducing image size may not reduce accuracy either. You should avoid fake high resolution in the photographs.

- **Photo quality:** You should aim the best photograph quality you can achieve without fake excess resolution. Higher quality photographs enable better point positioning. Try to avoid camera shake, defocus blur, over/under exposure.

- **Framing:** Try to take your photographs such that the scene of interest fills most of the frame; this way you can get higher positioning accuracy since you will get more pixels for the same distances.

- **Same camera for all photographs:** Try to take your photographs with the same camera, at the same focus length and same focus depth and same aperture; this way the calibration tool has fewer parameters to estimate, and you can get good accuracy with fewer matching points.

- **Have enough overlap in photographs:**

  - **Visible overlap:** For a 3D point to be a useful match point it has to appear in at least 2 photographs more, the better, therefore you can not rotate around your object/scene too much, between successive shots.

  - **Narrow angle pairs:** You should avoid photographs from very close vantage points. You should rotate around the scene/object enough to get good 3D information.

  - Avoid using too many photographs. It creates unnecessary burden on the user and the calibration tool.

  - The above three concerns generally contradict each other, and you should strike a balance. Fortunately Tgi3D® CT faithfully reports the achieved level of accuracy. You can increase photographs and matching points generally to meet your accuracy requirements.

- **Calibration points:** Your matching points should be well distributed in 2D and 3D. Avoid squeezing all you matching points to a small section in photographs. Also your matching points should be distributed in the volume of interest.

- **Number of matching points:** The more the better. Try to put around 10 points in each photograph.

- **Scale measurement choice:** Calibration tool is able to fathom relative distances only. Hence it needs an absolute distance reference, (that is you have to enter the distance between two 3D points) for scaling. You should use two good quality points (good visibility, low error) that more or less span your model. (that is your reference distance should not be too small compared with the rest of the distances.). Also note that the distances that are closer to the reference distance has better accuracy.

- **Feature selection:** Perceived features may shift due to exposure change, blur and partial/full saturation. Radially symmetric features (like the center of a small rectangle or a circle) are immune to that kind of shift. Prefer radially symmetric features, try to keep the exposure same, avoid nonlinear filtering to reduce errors introduced this way. We provide a feature pattern set of varying sizes. You can print them on sticky paper and use them as features with high accuracy.

- **Fixing erroneous matches:** After calibration is performed Tgi3D® CT reports point mismatch errors in descending order, You can inspect your marked points and make corrections if necessary. If there are enough calibration points Tgi3D® CT can work under even gross mismatch errors, (for example top of a building marked a bottom in another photograph). In case of a gross mismatch you will likely

be reported large mismatch errors. You should inspect the calibration points starting from the largest errors. The erroneous match does not have to be the largest error.

- **Transparent materials:** Avoid marking calibration points behind glass water etc. Even a very thin transparent material can introduce an apparent shift of several pixels, reducing the achievable accuracy.

- **Using rough calibration:** You can use a crude calibration to discover new matches. To do this you switch to 3D model and inspect 3D projections of calibrations in the photographs. You can select 3D points by left clicking them in 3D model view after which you can mark those points in additional photographs in which they are not already marked, and finally perform a match.