Reconstruction of 3-D Rigid Smooth Curves Moving Free when Two Traceable Points Only are Available

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1 Introduction

Reconstruction of shape of surrounding objects is a vital task to cope with by future (and partially by present) intelligent systems interacting with real world. In general, recovering of shapes of 3D space objects from 2D images [1, 2, 3, 4, 8, 16, 17, 20, 21, 28] has not been very successful as this task is too under-constrained (unless shape [5, 23], shading etc [7, 22] clues are available). Hence practical applications are rather based on sensing (via laser beams, ultrasonic methods etc. [18, 19]). Though successful in recovering shapes of surfaces, sensing fails to reconstruct curve-shaped objects as well as curved surface edges.

So this remains still a competition area for 2D projection based recognition methods. Some promising results were in fact achieved in recovering objects from multiframes (a time sequence of projections of the moving object) [6, 13, 24, 25, 26] as this task is over-constrained. Also in cases where features of interest cannot be all traced from frame to frame — e.g. smooth-curve shaped objects [9, 10, 11, 12, 14, 15, 27]. In fact, only several points (usually end points) are traceable, and the remaining ones are not. The strategy consists usually of two stages: reconstruction of space parameters of traceable points, thereafter reconstruction of non-traceable points.

This paper extends (in sections 3 & 4) previous results in that sense that for orthogonal projections of rigid smooth (true-3D) curves moving totally free it reduces the number of required traceable points to two only (the best results known so far to the author are 3 points from free motion and 2 for motion restricted to rotation around a fixed direction and and 2 for motion restricted to influence of a homogeneous force field). The method used is exploitation of information on tangential projections. Section 5 contains a remark on possibility of simplification of reconstruction of flat curves moving free for prospective projections.
2 Previous Work

The following table summarizes previous work in the area of reconstruction of rigid curves from multiframes under various shape and motion restrictions for orthogonal and prospective projections. Shift/rotation motion is “uniform” if in the same elapsed time the same amount of shift/rotation occurs. The motion is free if it does not fit this requirement of uniformity. A homogeneous force field causes the mass center point to have a constant acceleration vector.

| Motion Type                          | Number of traceable points | Number of Frames | Reference |
|--------------------------------------|-----------------------------|-----------------|-----------|
| FLAT (2D) CURVES IN 3D               |                             |                 |           |
| Orthogonal Projection                |                             |                 |           |
| free motion                          | 2                           | 2               | [12]      |
| Prospective Projection               | 3                           | 3               | [11]      |
| REAL 3D CURVES                       |                             |                 |           |
| Orthogonal Projection                |                             |                 |           |
| uniform rotational motion            | 2                           | 4               | [27, 12]  |
| free rotation around a               |                             |                 |           |
| fixed direction                      | 2                           | 4               | [9]       |
| free motion                          | 3                           | 3               | [9, 10]   |
| free motion, bounded by homogeneous  |                             |                 |           |
| force field                          |                             |                 |           |
| Prospective Projection               |                             |                 |           |
| rotation-free motion                 | 2                           | 2               | [9]       |
| uniform rotational motion            | 2                           | 5               | [9]       |
| free rotation around a               |                             |                 |           |
| fixed direction                      | 3                           | 3               | [9]       |
| free motion                          | 4                           | 3               | [9]       |
| free motion, bounded by homogeneous  |                             |                 |           |
| force field                          |                             |                 |           |
| Stereoscopic Vision                  |                             |                 |           |
| free motion                          | 2                           | 1               | [9, 28]   |

3 Reconstruction of Traceable Features

Let us characterize the traceables of the smooth curve. We assume that we can trace two points (usually endpoints) of it. Let the traceable points be $A$ and $B$. 
Figure 1: A smooth 3-D curve and its orthogonal projection

Their projections be called $A'_i$ and $B'_i$ ($i$ – frame index). Both $A'_i$ and $B'_i$ are observables. Furthermore we can observe the angles between $A'_iB'_i$ and the projections of tangentials at $A$ and $B$ being projections of angles between $AB$ and tangentials themselves (Fig.1). Let us call $\alpha$ the angle between $AB$ and the tangential at $B$, and $\beta$ the angle between $AB$ and tangential at $A$. $\phi$ be the angle between the plane containing $AB$ and tangential at $A$ and the plane containing $AB$ and the tangential at $B$.

Length of $AB$ be called $c$. $c$, $\alpha$, $\beta$, $\phi$ are fixed through all frames.

Let us consider the relation between the $i^{th}$ frame and the curve – especially the line $AB$ and the tangential at $B$. We can always imagine that the current position of the curve was achieved as follows:

1. At the beginning $A,B$ and tangential at $B$ lay in the frame plane in such a way that $A'_i = A$. Let us draw a straight line $l_1$ through in the frame place perpendicular to $AB$. Let $p1$ be the plane perpendicular to the frame plane and containing the line $l1$. (Fig.2).

2. First the curve is rotated by an angle $\delta_i$ around the by now line $AB$ (Fig. 3.). Let us fix on the tangential at $B$ the point $S$ at which by now the tangential crosses the plane $p1$. Let $S'$ be the orthogonal projection of $S$ in the plane $p1$ onto the line $l1$. Then we have: $\angle AS'S = 90^\circ$, $\angle SAS' = \delta_i$, $\angle ABS = \alpha$, hence:
Figure 2: The 3-D curve 'lying' on the projection plane

1) $\frac{AS}{AB} = \tan \alpha$
2) $\frac{AS}{AS'} = \cos \delta_i$
3) $\frac{SS'}{AB} = \sin \delta_i$

3. Thereafter we rotate the whole curve together with the point $S$ (not $S'$) around the line $l_1$ by the angle $\tau_i$ (Fig.4.). Let $S''$ be orthogonal projection of the newly positioned $S$ onto the frame plane. Then obviously $\angle BAB' = \tau_i$, $\angle S''S'A = 90^\circ$, $\angle SS'S'' = 90^\circ - \tau_i$. Hence:

4) $\frac{AB'}{AB} = \cos \tau_i$
5) $\frac{SS''}{SS'} = \cos(90^\circ - \tau_i)$

Let us denote by $D'$ the crossing point of the lines $l_1$ and $B'S''$. As we know the line $l_1$ and the direction of $B'S''$ (being the orthogonal projection of the tangential $BS$ at $B$), we know also the position of $D'$. We obtain:

6) $AS' = AD' + D'S'$
As $AB'$ is parallel to $S'S''$ (both in frame plane and both perpendicular to $l_1$) we get:

7) $\frac{AD'}{D'S'} = \frac{AB'}{S'S''}$
4. The shift of the whole curve from the projection frame in perpendicular direction (Fig. 5.) has no effect on the shape of projection and hence may be omitted from consideration.

Remark: we have dropped index i on primed and double primed points and on S to increase the legibility of formulas.

Summarizing, we obtained 7 equations in unknowns:

- $c = AB$, $\alpha$ — global for all frames
- $\tau_i$, $\delta_i$, $AS'$, $SS'$, $D'S'$, $S'S''$ — local for a frame

(as $A'$, $B'$ and $D'$ are visible, so $AB' = c_i$ and $AD' = d_i$ are known).

We derive eliminating $AS$ by (1):

- $2') AS' = \cos \delta_i \ast c \ast \tan \alpha$ and
- $3') SS' = \sin \delta_i \ast c \ast \tan \alpha$

Eliminating $AS'$ and $SS'$ by (2') and (3') we derive:

- $5'') S'S'' = \sin \tau_i \ast \sin \delta_i \ast c \ast \tan \alpha$ and
- $6'') \cos \delta_i \ast c \ast \tan \alpha = AD' + D'S'$

Eliminating $S'S''$ and $D'S'$ by (5'') and (6'') we obtain:
Figure 4: The 3-D curve rotated twice
Figure 5: The 3-D curve in space

\[
\frac{\cos \delta_i}{c \tan \alpha - AD'} = \frac{AB'}{\sin \tau_i \sin \delta_i \tan \alpha}
\]

Substituting (4) into (7‴) we get:

8) \( d'_i c \tan \alpha \sin \arccos(c'/c) \sin \delta_i c'_i c \tan \alpha \cos \delta_i - d'_i c'_i. \)

- one equation with one local (frame dependent) unknown \( \delta_i \).

However, by analogy, we can derive the second equation for the same frame considering the opposite side of the frame plane and the point \( B \) and the tangential at \( A \) instead of the point \( A \) and the tangential at the point \( B \). So we have the line \( l2 \) instead of \( l1 \) crossing \( B \), observable point \( E' \) (and edge \( BE' = e'_i \)) instead of \( D' \) (and \( d'_i \)). The rotation around \( l2 \) is the same as around \( l1 \) (i.e. \( \delta_i \)), but the rotation around \( AB \) must be \( \tau_i + \phi \), \( \phi \) being the angle between the plane containing \( AB \) and tangential at \( A \) and the plane containing \( AB \) and the tangential at \( B \) (fixed for all frames). So we obtain:

9) \( e'_i c \tan \beta \sin \arccos(c'/c) \sin(\delta_i + \phi) = c'_i c \tan \beta \cos(\delta_i + \phi) - e'_i c'_i. \)

Let us introduce auxiliary (frame) terms, containing only frame knowns and global unknowns:

\[
q_{i1} = c'_i c \tan \alpha, \quad p_{i1} = d'_i c \tan \alpha \sin \arccos(c'/c)
\]

\[
q_{i2} = c'_i c \tan \beta, \quad p_{i2} = e'_i c \tan \alpha \sin \arccos(c'/c)
\]

So we have the equation system:
10) \( p_{i1} \sin \delta_i = q_{i1} \cos \delta_i - d'_i c'_i. \)

11) \( p_{i2} \sin(\delta_i + \phi) = q_{i2} \cos(\delta_i + \phi) - e'_i c'_i. \)

Let us transform (10):

10') \( d'_i c'_i/\sqrt{p_{i1}^2 + q_{i1}^2} = \cos \delta_i q_{i1}/\sqrt{p_{i1}^2 + q_{i1}^2} - \sin \delta_i p_{i1}/\sqrt{p_{i1}^2 + q_{i1}^2} \)

If we introduce a new auxiliary variable \( \omega_{i1} \) (with global unknowns only)

\[ \omega_{i1} = \arctg (p_{i1}/q_{i1}) \]

then we have:

10'') \( d'_i c'_i/\sqrt{p_{i1}^2 + q_{i1}^2} = \cos (\delta_i + \omega_{i1}) \)

and by analogy:

11'') \( e'_i c'_i/\sqrt{p_{i2}^2 + q_{i2}^2} = \cos (\delta_i + \phi + \omega_{i2}) \)

and hence:

10''' \( \arccos(d'_i c'_i/\sqrt{p_{i1}^2 + q_{i1}^2}) = \delta_i + \omega_{i1} \)

11''' \( \arccos(e'_i c'_i/\sqrt{p_{i2}^2 + q_{i2}^2}) = \delta_i + \phi + \omega_{i2} \)

And thus we come to our final formula:

\[
12) \arccos(e'_i c'_i/\sqrt{p_{i2}^2 + q_{i2}^2}) - \arccos(d'_i c'_i/\sqrt{p_{i1}^2 + q_{i1}^2}) = \phi + \omega_{i2} - \omega_{i1}
\]

– one equation for each frame in unknowns: \( c, \alpha, \beta \) and \( \phi \), which does not contain any frame dependent unknown.

For determining all these four unknowns characterizing the reconstructed curve we need at least four frames.

Degenerated cases (parallelism of lines) are treated easily and will not be considered here.

The formula (12) is, regrettably, not a practical one, though the equation system is solvable. Therefore the result is more of theoretical importance than of practical one. However, it is possible to transform this formula into a (high degree) polynomial in \( c, \tg \alpha, \tg \beta \) and \( \tg \phi \), which can be a basis of a linear equation system constructed from a superfluous number of additionally observed frames, where the solution is based on conjecture of linear coefficient independence formulated in [10] and successfully applied therein to free motion under orthogonal projection with three traceable points and 3+1 frames.

Let us briefly outline the transformation of (12) into a lopynomial in the above-mentioned variables. After ”tangentializing” and squaring twice we obtain a quasi-polynomial of the form:

\[
12') s_2^2 + s_1^2 + y^2 + y^2 s_2^2 s_1^2 - 2s_1 s_2 - 2y s_2 - 2y s_2 s_1^2 - 2y s_1 - 2y s_2 s_1^2 - 2y^2 s_2 s_1 - 8y s_1 s_2 = 0
\]
with $y$ standing for

$$y = tg^2(\phi + \omega_2 - \omega_1)$$

and $s_1$, $s_2$ being proper polynomials:

$$s_1 = \frac{(d_i^2 + c_i^2)c^2tg\alpha - d_i^2c_i^2(tg^2\alpha - 1)}{d_i^2c_i^2}$$

$$s_2 = \frac{(e_i^2 + c_i^2)c^2tg\beta - e_i^2c_i^2(tg^2\beta - 1)}{e_i^2c_i^2}$$

So the only non-polynomial factor is $y$. However:

$$y = \frac{(d_i^2 - d_i^2)(c_i^2 - c_i^2)(tg^2\phi + 1)(1 + \frac{d_i}{c_i} - \frac{d_i}{c_i}) + tg\phi(\frac{e_i}{c_i} - \frac{e_i}{c_i})\sqrt{1 - c_i^2/c^2})^2}{((1 + d_i/c_i - d_i/c_i)^2 - tg2\phi(e_i/c_i - d_i/c_i)^2(1 - c_i^2/c^2))^2} - 1$$

So we obtain an equation of the form:

polynomial1 = polynomial2 * $\sqrt{(1 - c_i^2/c^2)}$

which is easily squared to obtain a proper polynomial in the above-mentioned variables.

To solve a system of equations being polynomials of high degree when superfluous observations from real world are available we proceed the following way: we transform the equations in the following form:

$$0 = \sum expression \in observables \cdot product \cdot of \ variables \ and \ their \ natural \ powers$$

We insist on each product \ of \ variables \ and \ their \ natural \ powers be different in each summand. For each product \ ... \ we introduce a new variable $a_k$ (something like the procedure when seeking a model for polynomial regression by means of linear regression method). In this way we obtain a linear equation system which we solve using Gaussian method (if the number of equations is equal to the number of new variables $a_i$ or by the least squares methods if the number of equations (that is, observed frames) is higher.

Solving such an equation system results in obtaining another one with equations of the form: productofvariables = constant, which after application of logarithm results in a new linear equation system, this time in variables of primary interest.

Why should this method (conjecture of linear coefficient independence) work? Of course, degenerate cases are possible. It works however the very same way the linear regression does: we usually observe much less variables than there are degrees of freedom in the real world.
4 Remark on Reconstruction of Non-Traceable Points

The formulas of previous section allow to identify the the relative (length c) as well as the absolute position of the feature points \(A, B\) as well as the (absolute and relative) direction of tangentials at \(A\) and \(B\) in space for each frame.

To recover the shape of the whole smooth curve, it is necessary to recover non-feature points also. It will be possible only if points \(A, B\) and tangentials are not co-planar. Then each point in space is defined by means of parameters \((p_1, p_2, p_3)\) as:

\[ A + p_1 \times AB + p_2 \times AC + p_3 \times AB \times AC \]

\( (O\) be the coordinate system origin) It is obvious that in case of rigidly connected points \(A, B, C\) every point and every straight line rigidly connected with them will retain the \((p_1, p_2, p_3, q_1, q_2, q_3)\) parameter set while the motion continues.

So let us select a point \(X_o\) in frame 0 lying in the projection plane on the projected curve (Fig.6.), this point being projection of a point \(X\) of the curve. We will succeed
with the reconstruction task for the point $X$ if we find out the distance $XX_0$ for the frame 0. $x$ be the name of the straight line connecting $X$ with $X_0$ (vertical to the projection plane). Let us obtain the parameters $p_1, p_2, p_3$ of this line and assume, that this line is fixed to the curve while moving. Let us draw now the projection of the line within the frame 1 obeying the function $f(u)$ for the frame 1 position of $A, B, C$. Then this projected line will cross the projected curve at some points one of them being the point $X_1$ – the projection of our point $X$ of the curve. (On ambiguity we can recall the continuity of the curve). As we know the equation of the straight line $XX_1$ in frame 1 as well as that of the straight line $x$ we can easily recover the distance $XX_1$, and later $XX_0$ of the first frame. Proceeding in this way we recover the whole curve. (Ambiguities are resolved by continuity requirement).

5 Flat Curves in Prospective Projection - A Remark

This work profited from analysis of Lee’s [12] method of reconstructing correspondence between two orthogonal projections of a flat curve in 3D. The basic idea there was that having two traceable (end)points of the curve we have in fact three of them: the third being the crossing point of tangentials at curve endpoints (as the curve is assumed “flat” that is planar, the tangentials – unless parallel – in fact have a common point). Then Lee simply exploited the Tales theorem in a straightforward way.

We would like to point out here that there is also a similar simple method for reconstruction of correspondence between two PROSPECTIVE projections of a flat curve in 3D, but three traceable points of the curve are required then. Though no better bound is achieved for the number of traceable points required than that in [11], however the computational effort is drastically reduced: Let the three traceable points be called $A, B, C$ (Fig. 7.). Clearly usually the tangentials at $A$ and $B$ share a point, say $D$. Let us call $E$ the common point of straight lines $AB$ and $DC$. Let $A', B', C', D', E$ be projections of $A, B, C, D, E$ respectively in the first frame, and $A'', B'', C'', D'', E''$ be respective projections in the second frame (Projections of $A, B$ and $C$ are visible, and projections of $D$ and $E$ are easily obtainable by drawing). Now let us consider $X'$, a projection of the non-traceable point $X$ of the curve in the first frame (let us select $X'$ freely on the curve projection image of the first frame.). We want to find $X''$ being the projection of $X$ in the second frame. Let us call $Y$ the common point of lines $AB$ and $DX$ — its projection $Y'$ can be obtained by drawing as crossing point of $A'B'$ and $D'X'$. Let us look for $Y''$ - the projection of $Y$ in the second frame. The well known elementary geometry theorem on perspective projection double quotient states that:

\[
15) \frac{AE}{AY} : \frac{BE}{BY} = \frac{A'E'}{A'Y'} : \frac{B'E'}{B'Y'}
\]

and

\[
16) \frac{AE}{AY} : \frac{BE}{BY} = \frac{A''E''}{A''Y''} : \frac{B''E''}{B''Y''}
\]

hence
As the positions of the remaining points $A'$, $B'$, $E'$, $Y'$, $A''$, $B''$, $E''$ are known, so based on (17) $Y''$ is easily found on the line $A''B''$. But $X''$ is the crossing point of the straight line $D''Y''$ and the image of curve projection in the second frame, so easy to find Q.E.D. (ambiguities are resolved by continuity requirement). Degenerated cases (parallelism of lines) are treated easily and will not be considered here.

6 Conclusions

This paper makes two basic contributions to solution of the problem of reconstruction of rigid smooth curves from multiframes:

1. decreases to 2 the theoretical lower bound on the number of traceable points required to reconstruct the shape of a true 3-D curve from multiframes under orthogonal projection with totally unpredictable motion assumed (the previous bound was either 3 points or 2 points with geometrical or physical restriction on freedom of motion)

2. introduces a new algorithm (based on double quotient) for reconstruction of flat curves in 3 D from multiframes under prospective projection using 3 traceable points, which is drastically simpler than that given in [11].
At this point the basic statement holding for all reconstruction algorithms based on multiframes should be repeated: unless the motion is a degenerate one (e.g. no motion at all, or no rotation at all, or rotation around an axis perpendicular to the frame plane etc.). If we compare the table given in Section 2 with the results of sections 3/4, we see easily that there is some ranking on the complexity of recovering algorithms depending on the amount and type of information available. E.g. from [9] we know that with 3 traceable points and three frames available we obtain an equation system with 3 mixed-quadratic equations in three variables. From [10] we know that adding one frame more leads us to an equation system with 3 linear equations in three variables. We can also observe that three point mean a special case of two points and two lines. From the complexity of equation (12) and the fact that 4 frames are required at least, however, we see that availability of two lines is a much weaker information that that stemming from a third point. Further research is necessary to simplify eventually the solution given in (12). Also we hope that exploiting some insights from consideration of flat curves in 3D under prospective projection also the bound of 4 traceable points necessary by now for true 3D curves may be broken in future research work.

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