Group algebra for robotic applications by means of operator overloading

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Abstract. Operator overloading is a powerful feature of modern object-oriented programming languages; it can be used to customize the default algebraic operators to a point where the programming syntax can accommodate new algebras acting on complex objects. The present work introduces a custom $\mathcal{T}(\mathbb{T}, \succ)$ algebra which can be used to express kinematic transformations in chains of frames that move in threedimensional space; relevant algebraic properties of $\mathcal{T}$ are discussed; finally the algebra is translated into a set of algorithms that can fit into the operator-overloading capabilities of the C++ language. Topics such as templates, serialization, optimizations and examples in the field mechanical simulation are discussed; moreover a novel method for run-time and compile-time validation of the syntax is exposed, so that the order of the products is checked for kinematic consistency - hence showing the advantage of this approach also for educational purposes.

Keywords. Kinematics, algebra, coordinates, robotics

1. Introduction

Object-oriented languages, such as C++ and Java among others, obtained increasing popularity in the field of software development, especially for large projects where complexity, maintenance, modularity and reusability are relevant issues (H. Sutter 2004). It is known that object-oriented languages lead to the organization of data and procedures (methods) in form of *classes* to whom the created run-time *objects* belong; moreover, one of the most interesting features of C++ and similar languages, is the ability of overloading operators between objects, so that common mathematical operators such as $+$, $-$, $*$, $/$, etc., can be customized in a sense that they can act over sophisticated objects, not only over floating point numbers. This motivates this work, where the operator-overloading capabilities of the C++ language are used to create an algebra between objects that represent moving references in three dimensional space.

Theoretical, applied and computational mechanics often require coordinate transformations, for instance one might need to compute the absolute position of points given their relative position respect to rigid frames which move in space (Hervé 1994). In this case, the transformation can be expressed as an affine map using matrix algebra or similar formalisms (Legnani, Casolo, Righettini & Zappa 1996).

Furthermore, one can consider the case of a sequence (kinematic chain) of moving frames, where the position of each frame is known respect to the previous one in the chain: the absolute position of the end of the chain can be expressed as a sequence of affine transformations based on the relative coordinates. This problem often happens in the field of robotics, multibody simulation, kinematics (Tasora & Righettini 2003). An usual and compact way to represent this kind of nested coordinate transformations is the Denavit-Hartenberg approach (M.W.Spong 1989), where 4x4 matrices are used to express rotations and translations with a single matrix multiplication on four-dimensional vectors; these matrices can be concatenated to express sequences of coordinate transformations as in robotic arms.

The algebra discussed herewith encompasses also speeds and accelerations: in fact if in a chain of frames also the relative speed and relative acceleration of each frame is known respect to the previous frame in the chain, a formalism can be developed to find the

absolute position, speed and acceleration of the end of the chain.

We define a $\succ$ operator such that a sequence of $\succ$ operations corresponds to a chain of coordinate transformations. An example can explain this: consider $\chi_{i,(j)}$ as a data that represent the position, speed and acceleration (either linear and angular) of the frame i respect to coordinate j; thus, a sequence of transformations as in the example of Fig.1 can be written as:

$$\chi_{3,(0)} = \chi_{3,(2)} \succ \chi_{2,(1)} \succ \chi_{1,(0)}. \quad (1)$$

Among other things, one can use the previous transformation to compute $\mathbf{r}_{3,(0)}$, i.e the absolute position of the origin of 3 respect to the absolute coordinate system 0, because

$$\chi_{3,(0)} = \{\mathbf{r}_{3,(0)}, \mathbf{q}_{3,(0)}, \dot{\mathbf{r}}_{3,(0)}, \omega_{3,(0)}, \ddot{\mathbf{r}}_{3,(0)}, \alpha_{3,(0)}\}.$$

Of course a similar result can be obtained using linear algebra, for example using the Denavit-Hartenberg formalism, (Shabana 1989), however we remark that the approach discussed in these pages is more compact and encompasses speed and acceleration transformations in a single operation. For instance, the absolute speed of 3 is also contained in $\chi_{3,(0)}$, and depends on angular velocities and speeds of all other systems in the chain.

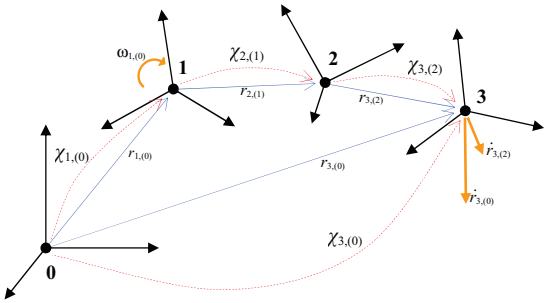

Figure 1: Example of chained transformation

2. Introducing the $\mathcal{T}(\mathbb{T}, \succ)$ algebra

It is known (Selig 2005)(Hervé 1999) that the so called special Euclidean group of rigid transformations in three dimensional space, $\mathsf{SE}(3)$, is the semi-direct product of the two Lie soubgroups: $\mathsf{SO}(3)$, the Lie group of isometries with fixed point (Kolev 2004), and $\mathbb{R}^3$, for translations; that is $\mathsf{SE}(3) = \mathsf{SO}(3) \rtimes \mathbb{R}^3$.

Aiming at a group algebra that succintly transforms also velocities and accelerations, we introduce the group $\mathcal{T}^{\mathsf{SO}}(\mathbb{T}^{\mathsf{SO}}, \succ)$ whose non-abelian operator $\succ$ acts over a 18-dimensional manifold

$$\mathbb{T}^{\mathsf{SO}} = \{\mathbb{R}^3 \rtimes \mathsf{SO}(3) \rtimes \mathbb{R}^6 \rtimes \mathbb{R}^6\}.$$

The $\succ$ operator has arity $\bar{\alpha} = 2$.

This algebra will be used to manage coordinate transformations: each element $\chi \in \mathbb{T}^{\mathsf{SO}}$ can represent a frame in three-dimensional space, including position, rotation information, as well as speed and acceleration information.

Here we remark that, although rotations could be parametrized with a set of three angles, it is well known that, given the topology $\mathsf{SO}(3)$, this could cause problems of singularities because $\mathbb{R}^3$ is not omeomorphic to $\mathsf{SO}(3)$. Therefore we parametrize $\mathsf{SO}(3)$ with unitary quaternions $\mathbf{q} \in \mathsf{S}^3$, i.e. $\mathbf{q} \in \mathbb{H}_1$, whose adoption in the context of computer simulation proved to be very reliable and practical. The only drawback is that S^3 is not exactly isomorphic to $\mathsf{SO}(3)$, being its double cover. Yet this is not a big issue (the only drawback is that there are two distinct quaternions per a single rotation), so we can rather work with an epimorphism of $\mathcal{T}^{\mathsf{SO}}(\mathbb{T}^{\mathsf{SO}}, \succ)$, that is $\mathcal{T}(\mathbb{T}, \succ)$, using quaternions:

$$\mathbb{T} = \{\mathbb{R}^3 \rtimes \mathsf{S}^3 \rtimes \mathbb{R}^6 \rtimes \mathbb{R}^6\}.$$

The speed of the origin of the frame is denoted with $\dot{\mathbf{r}} \in \mathbb{R}^3$, its angular speed is denoted with $\omega \in \mathbb{R}^3$ (expressed in the base of the moving frame). Similarly we denote acceleration with $\ddot{\mathbf{r}}$ and angular acceleration with α, the latter being expressed in the local base of the moving frame. Thus, we define the vector $\chi \in \mathbb{T}$ for $\mathbf{r} \in \mathbb{R}^3$, $\mathbf{q} \in \mathsf{S}^3$, $\dot{\mathbf{r}}, \omega, \ddot{\mathbf{r}}, \alpha \in \mathbb{R}^3$, as :

$$\chi = \{\mathbf{r}, \mathbf{q}, \dot{\mathbf{r}}, \omega, \ddot{\mathbf{r}}, \alpha\}.$$

From now on, assuming that position, rotation, speed and acceleration of a frame a in χ_a are expressed relative to another frame b, we will use the notation $\chi_{a,(b)}$. Also, we will denote the frame b as the *parent frame* of a or, similarly, a as the *child frame* of b. The definition of the $\succ$ operation stems from the requirement that

$$\begin{matrix} \chi_{a,(c)} = & \chi_{a,(b)} \succ & \chi_{b,(c)} \end{matrix}$$
$$\begin{Bmatrix} \mathbf{r}_{a,(c)} \\ \mathbf{q}_{a,(c)} \\ \dot{\mathbf{r}}_{a,(c)} \\ \omega_{a,(c)} \\ \ddot{\mathbf{r}}_{a,(c)} \\ \alpha_{a,(c)} \end{Bmatrix} = \begin{Bmatrix} \mathbf{r}_{a,(b)} \\ \mathbf{q}_{a,(b)} \\ \dot{\mathbf{r}}_{a,(b)} \\ \omega_{a,(b)} \\ \ddot{\mathbf{r}}_{a,(b)} \\ \alpha_{a,(b)} \end{Bmatrix} \succ \begin{Bmatrix} \mathbf{r}_{b,(c)} \\ \mathbf{q}_{b,(c)} \\ \dot{\mathbf{r}}_{b,(c)} \\ \omega_{b,(c)} \\ \ddot{\mathbf{r}}_{b,(c)} \\ \alpha_{b,(c)} \end{Bmatrix} \quad (2)$$

By applying expressions for kinematic transformations in three dimensional space, in the following subsections we develop the expressions for the terms in Eq.(2).

2.1. Product: position and rotation part

As known (Shabana 1989), the morphism

$$\mathbf{q}_r^o = \mathbf{q}_e \mathbf{q}_r \mathbf{q}_e^*. \quad (3)$$

is $||\cdot||_2$-norm preserving and rotates a quaternion $\mathbf{q}_r \in \mathbb{H}$ by means of an unimodular quaternion $\mathbf{q}_e \in \mathsf{S}^3$ and its conjugate $\mathbf{q}_e^*$.

Expression (3) can be used to rotate points in space, with rotation represented in form of Euler parameters $\mathbf{q}_e$ and $\mathbf{q}_r$ as a so-called *pure* quaternion with imaginary part as the cartesian coordinates of a point:

$$\mathbf{q}_r = \Im(\mathbf{r}) \equiv \{0, r_x, r_y, r_z\}.$$

Therefore, the affine transformation of the point $\mathbf{r}_{a,(b)}$ after rotation $\mathbf{q}_{b,(c)}$ and translation $\mathbf{r}_{b,(c)}$ can be expressed as:

$$\Im(\mathbf{r}_{a,(c)}) = \Im(\mathbf{r}_{b,(c)}) + \mathbf{q}_{b,(c)}\Im(\mathbf{r}_{a,(b)})\mathbf{q}^*_{b,(c)}. \quad (4)$$

This Eq.(4) has a counterpart in linear algebra:

$$\mathbf{r}_{a,(c)} = \mathbf{r}_{b,(c)} + [A(\mathbf{q}_{b,(c)})]\mathbf{r}_{a,(b)}. \quad (5)$$

where we introduced the rotation matrix $[A(\mathbf{q}_{b,(c)})]$ function of a quaternion $\mathbf{q}_{b,(c)}$ as described, for instance, in (Shabana 1989).

The term $\mathbf{q}_{a,(c)}$, representing the rotation of the reference a respect to the reference c, can be easily obtained with a single quaternion product:

$$\mathbf{q}_{a,(c)} = \mathbf{q}_{b,(c)}\mathbf{q}_{a,(b)} \quad (6)$$

as can be seen applying the affine map (4) twice, for transforming a point p from reference a to reference b and from reference b to reference c:

$$\begin{aligned}\Im(\mathbf{r}_{p,(c)}) =& \Im(\mathbf{r}_{b,(c)}) + \mathbf{q}_{b,(c)}\left(\Im(\mathbf{r}_{a,(b)}) + \right.\\ & \left.\mathbf{q}_{a,(b)}\Im(\mathbf{r}_{p,(a)})\mathbf{q}^*_{a,(b)}\right)\mathbf{q}^*_{b,(c)}\\ =& \Im(\mathbf{r}_{b,(c)}) + \mathbf{q}_{b,(c)}\Im(\mathbf{r}_{a,(b)})\mathbf{q}^*_{b,(c)} +\\ & \mathbf{q}_{b,(c)}\mathbf{q}_{a,(b)}\Im(\mathbf{r}_{p,(a)})\mathbf{q}^*_{a,(b)}\mathbf{q}^*_{b,(c)}\\ =& \Im(\mathbf{r}_{a,(c)}) + \mathbf{q}_{a,(c)}\Im(\mathbf{r}_{p,(a)})\mathbf{q}^*_{a,(c)}.\end{aligned}$$

2.2. Product: the velocity part

Speed terms $\dot{\mathbf{r}}_{a,(c)}$ and $\omega_{a,(c)}$ can be obtained from symbolic differentiation of Eq.(4) and Eq.(6). By applying the chain rule to the differentiation of the affine map of Eq.(4):

$$\begin{aligned}\dot{\Im}(\mathbf{r}_{a,(c)}) =& \dot{\Im}(\mathbf{r}_{b,(c)}) + \dot{\mathbf{q}}_{b,(c)}\Im(\mathbf{r}_{a,(b)})\mathbf{q}^*_{b,(c)} +\\ & \mathbf{q}_{b,(c)}\dot{\Im}(\mathbf{r}_{a,(b)})\mathbf{q}^*_{b,(c)} + \mathbf{q}_{b,(c)}\Im(\mathbf{r}_{a,(b)})\dot{\mathbf{q}}^*_{b,(c)}\\ \dot{\Im}(\mathbf{r}_{a,(c)}) =& \dot{\Im}(\mathbf{r}_{b,(c)}) + 2\dot{\mathbf{q}}_{b,(c)}\Im(\mathbf{r}_{a,(b)})\mathbf{q}^*_{b,(c)} +\\ & \mathbf{q}_{b,(c)}\dot{\Im}(\mathbf{r}_{a,(b)})\mathbf{q}^*_{b,(c)}\end{aligned}$$

We note that $\dot{\Im}(\mathbf{r}) = \Im(\dot{\mathbf{r}})$, hence we get:

$$\begin{aligned}\Im(\dot{\mathbf{r}}_{a,(c)}) =& \Im(\dot{\mathbf{r}}_{b,(c)}) + 2\dot{\mathbf{q}}_{b,(c)}\Im(\mathbf{r}_{a,(b)})\mathbf{q}^*_{b,(c)} +\\ & \mathbf{q}_{b,(c)}\Im(\dot{\mathbf{r}}_{a,(b)})\mathbf{q}^*_{b,(c)}.\end{aligned} \quad (7)$$

Similarly, one can perform the time derivative of the expression of Eq.(6):

$$\dot{\mathbf{q}}_{a,(c)} = \dot{\mathbf{q}}_{b,(c)}\mathbf{q}_{a,(b)} + \mathbf{q}_{b,(c)}\dot{\mathbf{q}}_{a,(b)}. \quad (8)$$

The angular velocity $\omega_{a,(c)}$ of $\chi_{a,(c)}$, expressed in the coordinates of reference a, follows immediately the quaternion derivative $\dot{\mathbf{q}}_{a,(c)}$ obtained with Eq.(8) using the following formula, discussed in (Shabana 1989):

$$\Im(\omega_{a,(c)}) = 2\mathbf{q}^*_{a,(c)}\dot{\mathbf{q}}_{a,(c)}. \quad (9)$$

2.3. Product: the acceleration part

The last two parts of the $\chi_{a,(c)}$ vector are the acceleration $\ddot{\mathbf{r}}_{a,(c)}$ and the angular acceleration $\alpha_{a,(c)}$.

By differentiation of Eq.(7):

$$\begin{aligned}\ddot{\Im}(\mathbf{r}_{a,(c)}) =& \ddot{\Im}(\mathbf{r}_{b,(c)}) +\\ & 2\ddot{\mathbf{q}}_{b,(c)}\Im(\mathbf{r}_{a,(b)})\mathbf{q}^*_{b,(c)} +\\ & 2\dot{\mathbf{q}}_{b,(c)}\dot{\Im}(\mathbf{r}_{a,(b)})\mathbf{q}^*_{b,(c)} +\\ & 2\dot{\mathbf{q}}_{b,(c)}\Im(\mathbf{r}_{a,(b)})\dot{\mathbf{q}}^*_{b,(c)} +\\ & + \dot{\mathbf{q}}_{b,(c)}\dot{\Im}(\mathbf{r}_{a,(b)})\mathbf{q}^*_{b,(c)} +\\ & \mathbf{q}_{b,(c)}\ddot{\Im}(\mathbf{r}_{a,(b)})\mathbf{q}^*_{b,(c)} +\\ & \mathbf{q}_{b,(c)}\dot{\Im}(\mathbf{r}_{a,(b)})\dot{\mathbf{q}}^*_{b,(c)}\\ =& \ddot{\Im}(\mathbf{r}_{b,(c)}) +\\ & 2\ddot{\mathbf{q}}_{b,(c)}\Im(\mathbf{r}_{a,(b)})\mathbf{q}^*_{b,(c)} +\\ & 4\dot{\mathbf{q}}_{b,(c)}\dot{\Im}(\mathbf{r}_{a,(b)})\mathbf{q}^*_{b,(c)} +\\ & + 2\dot{\mathbf{q}}_{b,(c)}\Im(\mathbf{r}_{a,(b)})\dot{\mathbf{q}}^*_{b,(c)} +\\ & \mathbf{q}_{b,(c)}\ddot{\Im}(\mathbf{r}_{a,(b)})\mathbf{q}^*_{b,(c)}\end{aligned}$$

and finally, as $\ddot{\Im}(\mathbf{r}_{a,(c)}) = \Im(\ddot{\mathbf{r}}_{a,(c)})$, it is:

$$\begin{aligned}\Im(\ddot{\mathbf{r}}_{a,(c)}) =& \Im(\ddot{\mathbf{r}}_{b,(c)}) + 2\ddot{\mathbf{q}}_{b,(c)}\Im(\mathbf{r}_{a,(b)})\mathbf{q}^*_{b,(c)} +\\ & 4\dot{\mathbf{q}}_{b,(c)}\Im(\dot{\mathbf{r}}_{a,(b)})\mathbf{q}^*_{b,(c)} +\\ & + 2\dot{\mathbf{q}}_{b,(c)}\Im(\mathbf{r}_{a,(b)})\dot{\mathbf{q}}^*_{b,(c)} +\\ & \mathbf{q}_{b,(c)}\Im(\ddot{\mathbf{r}}_{a,(b)})\mathbf{q}^*_{b,(c)}\end{aligned} \quad (10)$$

Interms of quaternion derivative, angular acceleration follow from the differentiation of the epression of Eq.(8):

$$\begin{aligned}\ddot{\mathbf{q}}_{a,(c)} =& \ddot{\mathbf{q}}_{b,(c)}\mathbf{q}_{a,(b)} + \dot{\mathbf{q}}_{b,(c)}\dot{\mathbf{q}}_{a,(b)} +\\ & \dot{\mathbf{q}}_{b,(c)}\dot{\mathbf{q}}_{a,(b)} + \mathbf{q}_{b,(c)}\ddot{\mathbf{q}}_{a,(b)}\\ =& \ddot{\mathbf{q}}_{b,(c)}\mathbf{q}_{a,(b)} + 2\dot{\mathbf{q}}_{b,(c)}\dot{\mathbf{q}}_{a,(b)} + \mathbf{q}_{b,(c)}\ddot{\mathbf{q}}_{a,(b)}\end{aligned} \quad (11)$$

As a vector, the classical angular acceleration $\alpha_{a,(c)}$ of $\chi_{a,(c)}$, expressed in the coordinates of reference a, is obtained from the quaternion $\ddot{\mathbf{q}}_{a,(c)}$ of Eq.(11) and from the differentiation of Eq.(9):

$$\Im(\alpha_{a,(c)}) = 2\dot{\mathbf{q}}^*_{a,(c)}\dot{\mathbf{q}}_{a,(c)} + 2\mathbf{q}^*_{a,(c)}\ddot{\mathbf{q}}_{a,(c)} \quad (12)$$

3. Main properties

After having defined the product of the $\mathcal{T}(\mathbb{T}, \succ)$ algebra, in this section we will outline some of its properties.

- The manifold $\mathbb{T}$ is a topological space,

- The entire $\mathbb{T}$ is a double cover of $\mathbb{T}^{\mathsf{SO}} = \{\mathbb{R}^3 \rtimes \mathsf{SO}(3) \rtimes \mathbb{R}^{12}\}$ because of the epimorphism (surjective homeomorphism) $r : \mathsf{S}^3 \to \mathsf{SO}(3,\mathbb{R})$. It is also isomorphic to $\mathbb{T}^{\mathsf{SU}} = \{\mathbb{R}^3 \rtimes \mathsf{SU}(2) \rtimes \mathbb{R}^{12}\}$.

- The $\mathcal{T}(\mathbb{T},\succ)$ algebra is a Lie group with $\dim_{/\mathbb{R}} = 18$, It acts on a smooth manifold (Weyl 1950) and it has the properties of closure, associativity, identity, existence of inverse element. This will be shown later in detail.

- The Lie group *left-translation* (Souriau 2008) is computed as $L_{\chi_a}\chi_b = \chi_a \succ \chi_b$, using the formulas developed in the previous section. Similarly, the *right-translation* is computed as $R_{\chi_a}\chi_b = \chi_b \succ \chi_a$.

In the following we present two theorems showing the fact that, as a Lie algebra, $\mathcal{T}(\mathbb{T},\succ)$ has a neutral element and an inverse element.

THEOREM 1

The $\mathcal{T}(\mathbb{T},\succ)$ algebra has an identity element $\chi_I \in \mathbb{T}$.

Proof. Let consider an element $\chi_I \in \mathbb{T}$ as $\chi_I = \{\mathbf{0}, \mathbf{q}_I, \mathbf{0}, \mathbf{0}, \mathbf{0}, \mathbf{0}\}$, where $\mathbf{q}_I$ is the unitary quaternion $1 + 0i + 0j + 0k$.

The product $\chi_a = \chi_b \succ \chi_I$ gives $\chi_a = \{\mathbf{r}_a, \mathbf{q}_a, \dot{\mathbf{r}}_a, \omega_a, \ddot{\mathbf{r}}, \alpha_a\}$. According to the definition of Eq.(4), the position term can be made explicit as:

$$\Im(\mathbf{r}_a) = \Im(\mathbf{0}) + \mathbf{q}_I \Im(\mathbf{r}_b)\mathbf{q}_I^*.$$

Since $\mathbf{q}_I \Im(\mathbf{r}_b)\mathbf{q}_I^* = \Im(\mathbf{r}_b)$ by property of quaternion multiplication, it is also

$$\Im(\mathbf{r}_a) = \Im(\mathbf{r}_b) \tag{13}$$

Also, Eq.(6) becomes

$$\mathbf{q}_a = \mathbf{q}_I \mathbf{q}_b = \mathbf{q}_b. \tag{14}$$

Similarly, one can made explicit the speed and acceleration terms using definitions (7, 8), 10, 11): by exploiting the aforementioned properties of quaternion multiplications, it is clear that most terms vanish:

$$\begin{aligned}
\Im(\dot{\mathbf{r}}_a) =& \Im(\mathbf{0}) + 2(\mathbf{0}\Im(\mathbf{r}_b)\mathbf{q}_I^*) + \\
& \mathbf{q}_I \Im(\dot{\mathbf{r}}_b)\mathbf{q}_I^* = \Im(\dot{\mathbf{r}}_b) && (15)\\
\dot{\mathbf{q}}_a =& \mathbf{0}\mathbf{q}_b + \mathbf{q}_I \dot{\mathbf{q}}_b = \dot{\mathbf{q}}_b && (16)\\
\Im(\ddot{\mathbf{r}}_a) =& \mathbf{0} + 2(\mathbf{0}\Im(\mathbf{r}_b)\mathbf{q}_I^*) + \\
& 4(\mathbf{0}\Im(\dot{\mathbf{r}}_b)\mathbf{q}_I^*) + 2(\mathbf{0}\Im(\mathbf{r}_b)\mathbf{0}^*) + \\
& \mathbf{q}_I \Im(\ddot{\mathbf{r}}_b)\mathbf{q}_I^* = \Im(\ddot{\mathbf{r}}_b) && (17)\\
\ddot{\mathbf{q}}_a =& \mathbf{0}\mathbf{q}_b + 2(\mathbf{0}\dot{\mathbf{q}}_b) + \mathbf{q}_I \ddot{\mathbf{q}}_b = \ddot{\mathbf{q}}_b. && (18)
\end{aligned}$$

Thus, from Eq.(13-18) and properties (9),(12), it follows that $\chi_a = \chi_b \succ \chi_I = \chi_b$, so $\succ \chi_I$ is the right-neutral element of the $\mathcal{T}(\mathbb{T},\succ)$ algebra.

For reasons of space, we do not develop the product $\chi_a = \chi_b \succ \chi_I$; it would be easy to obtain again the same results of Eq.(13-18), although using other properties of quaternion algebra for the cancellation of the terms. Hence it follows that χ_I is also a left-neutral element in the $\mathcal{T}(\mathbb{T},\succ)$ algebra.

Give that the magma has both right and left-neutral elements, $\mathcal{T}(\mathbb{T},\succ)$ is also a monoid with $\chi_b \succ \chi_I = \chi_I \succ \chi_b = \chi_b$. QED.

The proof of the following theorem is also useful to get an explicit expression for the inverse element. Moreover, as expected, the commutative property does not hold:

THEOREM 2

The $\mathcal{T}(\mathbb{T},\succ)$ algebra is a non-abelian group.

Proof.

For the $\mathcal{T}(\mathbb{T},\succ)$ monoid algebra to be a group, each element χ must have an inverse element χ^{-1} such that $\chi^{-1} \succ \chi = \chi_I$, where χ_I is the neutral elment introduced in Theorem 1.

For semplicity, let's recall the notation of the product in Eq.(2). If $\chi_{a,(b)} \succ \chi_{b,(c)} = \chi_I$, then $\chi_{a,(b)}$ is the left-inverse of $\chi_{b,(c)}$, and will be denoted as $\chi_{b,(c)}^{-1L}$. Also, $\chi_{b,(c)}$ is the right-inverse of $\chi_{a,(b)}$, and will be denoted as $\chi_{a,(b)}^{-1R}$. Thus, if right and left inverses exist,

$$\chi_{a,(b)} \succ \chi_{a,(b)}^{-1R} = \chi_I, \quad \chi_{b,(c)}^{-1L} \succ \chi_{b,(c)} = \chi_I$$

Imposing $\chi_{a,(c)} = \chi_I$ in the product of Eq.(2), one can write $\chi_{a,(b)} \succ \chi_{b,(c)} = \chi_I$, then it will be possible to manipulate the definitions in Eq.(4-11) to find the expression of the left-inverse by explicitating the terms belonging to $\chi_{a,(b)}$.

Let start from the transformation of positions. We rewrite Eq.(4) as:

$$\Im(\mathbf{r}_{b,(c)}) + \mathbf{q}_{b,(c)} \Im(\mathbf{r}_{a,(b)}) \mathbf{q}_{b,(c)}^* = \Im(\mathbf{0}).$$

Let left-multiply all terms by quaternion $\mathbf{q}_{b,(c)}^{-1}$ and right-multiply all terms by $\mathbf{q}_{b,(c)}^{*-1}$. By remembering quaternion algebra properties $\mathbf{q}\mathbf{q}^{-1} = \{1,0,0,0\}$ and $\mathbf{q}\{1,0,0,0\} = \mathbf{q}$, $\mathbf{q} \in \mathbb{H}_1$, it is easy to find:

$$\Im(\mathbf{r}_{a,(b)}) = -\mathbf{q}_{b,(c)}^{-1} \Im(\mathbf{r}_{b,(c)}) \mathbf{q}_{b,(c)}^{*-1}. \tag{19}$$

This is the first element of the left-inverse vector, that in our proof is $\chi_{a,(b)} = \chi_{b,(c)}^{-1L}$.

Coming to rotations, remembering that the rotation part $\mathbf{q}$ in the neutral element χ_I is the unit quaternion $\{1,0,0,0\}$ as demonstrated in Theorem 1, we rewrite Eq.(6) as follows:

$$\mathbf{q}_{b,(c)} \mathbf{q}_{a,(b)} = \{1,0,0,0\}.$$

Therefore, using quaternion inverses, premultiplying the terms by $\mathbf{q}_{b,(c)}^{-1}$ and simplifying, one gets the

rotational part of the left-inverse:

$$\mathbf{q}_{a,(b)} = \mathbf{q}_{b,(c)}^{-1}. \tag{20}$$

Now set Eq.(7) to zero in order to compute the speed part of the inverse:

$$\Im(\dot{\mathbf{r}}_{b,(c)}) + 2\dot{\mathbf{q}}_{b,(c)}\Im(\mathbf{r}_{a,(b)})\mathbf{q}_{b,(c)}^{*} + \mathbf{q}_{b,(c)}\Im(\dot{\mathbf{r}}_{a,(b)})\mathbf{q}_{b,(c)}^{*} = \Im(\mathbf{0})$$

Here, few manipulations with quaternion algebra will produce the following result:

$$\Im(\dot{\mathbf{r}}_{a,(b)}) = \mathbf{q}_{b,(c)}^{-1}(-\Im(\dot{\mathbf{r}}_{b,(c)}) + 2\dot{\mathbf{q}}_{b,(c)}\mathbf{q}_{b,(c)}^{-1}\Im(\mathbf{r}_{b,(c)}))\mathbf{q}_{b,(c)}^{*-1}. \tag{21}$$

Also, imposing that $\dot{\mathbf{q}}_{a,(c)}$ is null in Eq.(8), it follows:

$$\dot{\mathbf{q}}_{a,(b)} = -\mathbf{q}_{b,(c)}^{-1}\dot{\mathbf{q}}_{b,(c)}\mathbf{q}_{b,(c)}^{-1}. \tag{22}$$

With similar algebraic manipulations, and remembering that $\mathbf{q}^{*-1}\mathbf{q}^{*} = \{1,0,0,0\}$, one can get the accleration part of the left inverse, obtaining:

$$\begin{aligned}\Im(\ddot{\mathbf{r}}_{a,(b)}) = &\mathbf{q}_{b,(c)}^{-1}[-\Im(\ddot{\mathbf{r}}_{b,(c)}) + 2\ddot{\mathbf{q}}_{b,(c)}\mathbf{q}_{b,(c)}^{-1}\Im(\mathbf{r}_{b,(c)}) \\ &+ 4\dot{\mathbf{q}}_{b,(c)}\mathbf{q}_{b,(c)}^{-1}(\Im(\dot{\mathbf{r}}_{b,(c)}) \\ &- 2\dot{\mathbf{q}}_{b,(c)}\mathbf{q}_{b,(c)}^{-1}\Im(\mathbf{r}_{b,(c)})) \\ &+ 2\dot{\mathbf{q}}_{b,(c)}\mathbf{q}_{b,(c)}^{-1}\Im(\mathbf{r}_{b,(c)})\mathbf{q}_{b,(c)}^{-1}\dot{\mathbf{q}}_{b,(c)}^{*}]\mathbf{q}_{b,(c)}^{*-1}\end{aligned}$$

and

$$\ddot{\mathbf{q}}_{a,(b)} = \mathbf{q}_{b,(c)}^{-1}(\ddot{\mathbf{q}}_{b,(c)} - 2\dot{\mathbf{q}}_{b,(c)}\mathbf{q}_{b,(c)}^{-1}\dot{\mathbf{q}}_{b,(c)})\mathbf{q}_{b,(c)}^{-1}. \tag{23}$$

Finally, using Eq.(9) and Eq.(12), one can merge Eq.(19-23) into $\chi_{a,(b)}$, that is the left-inverse $\chi_{b,(c)}^{-1L}$ which satisfies $\chi_{a,(b)} \succ \chi_{b,(c)} = \chi_{b,(c)}^{-1L} \succ \chi_{b,(c)} = \chi_I$.

Similarly, we could solve $\chi_{a,(b)} \succ \chi_{b,(c)} = \chi_I$ for $\chi_{b,(c)}$: after long symbolic manipulation (not reported in these pages in sake of compactness) we would obtain the same results of Eq.(19-23), but with inverted subscripts, that is with $a,(b)$ swapped with $b,(c)$. Therefore, we built the right-inverse $\chi_{a,(b)}^{-1R}$ and we conclude that, for a generic element $\chi \in \mathbb{T}$, right- and left-inverses are the same, that is $\chi^{-1R} = \chi^{-1L} = \chi^{-1}$. Given the existence of the inverse, the algebra is a group.

Although associative, the group is non-abelian since the $\succ$ operation is non commutative: this follows from the fact that quaternion algebra is a skew field. QED.

4. Software implementation

Efficiency and the correctness of the theoretical framework has been tested by implementing a set of software libraries for coordinate transformation using the C++ language. A similar approach is described in (Legnani et al. 1996).

Our framework exploits the objects oriented paradigm, so $\chi \in \mathbb{T}$ elements are represented by objects inherited from a C++ class which we named `ChMovingFrame`.

Moreover, a subset of the methods exposed here has been implemented in a simpler C++ class called `ChFrame`, that deals only with the translation and rotation and carries no information about velocities and accelerations. The `ChFrame` class is also the parent class of `ChMovingFrame`, because it shares many methods and formulas about rotations and translations. Then the `ChMovingFrame` specializes the methods and the operators for the case when also velocities and accelerations are used [1].

After extensive benchmarking, we concluded that it is more convenient to work with objects where angular speeds and angular accelerations are represented directly with quaternions $\dot{\mathbf{q}}$ and $\ddot{\mathbf{q}}$ rather than with 3D vectors ω and α. Thank to the encapsulation paradigm of OOP, this design does not affect the way the programmer interacts with the data, because custom functions can provide ω and α only when requested, by evaluating Eq.(9) and Eq.(12). Viceversa, the user can provide ω or α, and these are instantly converted to $\dot{\mathbf{q}}$ and $\ddot{\mathbf{q}}$ using inverse formulas.

Since we used this software library in many engineering projects, we were able to make a statistical analysis and we found that, in most cases, an object of `ChMovingFrame` class is used simply to transform 3D points, and only in few cases one is interested also in speeds and accelerations. This means that the most important function is the one in Eq.(4), which we implemented in different flavours for optimal execution speed. For example, if a single object of `ChMovingFrame` type must transform many 3D vectors at once, we can use Eq.(5), which is a bit faster than Eq.(4) because rotation by matrix-vector multiplication (after the matrix has been initialized once, with the nine values) takes less time than computing the quaternion endomorphism. However this optimization implies that a 3x3 matrix is stored in the `ChMovingFrame` object, for easing the case of multiple point transformations; the nine values of the matrix are recomputed when the rotation of the frame changes. The improved performance is worth while the overhead of keeping such matrix updated, and the increased memory requirement.

So far, each `ChMovingFrame` object contains three vectors, three quaternions and an auxiliary 3x3 matrix:

$$\chi_{c++} = \{\mathbf{r}, \mathbf{q}, [A(\mathbf{q})], \dot{\mathbf{r}}, \dot{\mathbf{q}}, \ddot{\mathbf{r}}, \ddot{\mathbf{q}}\}.$$

The `ChFrame` object contains only $\mathbf{r}$, $\mathbf{q}$, $[A(\mathbf{q})]$.

An useful feature of the C++ language is the *oper-*

[1] In this way, depending on the problem type, the developer can choose when using a fast `ChFrame` object or a more powerful but slower `ChMovingFrame`.

ator overloading, wich allows a straightforward mapping of the $\mathcal{T}(\mathbb{T}, \succ)$ algebra into a new programming syntax where the $\succ$ operator can be represented as a binary operator between two `ChMovingFrame` objects. To avoid confusion with default operators `*,+,-,/`, we decided to use the `>>` symbol to represent the $\succ$ operation.

Such operation is implemented in the header of the `ChMovingFrame` class, using the following binary operator overloading:

```
ChFrameMoving<Real> operator >> (...)
```

In the function above, the formulas in Eq.(4-11) are evaluated, where the return value represents the resulting vector $\chi_{a,(c)}$, the object itself (the `this` pointer) is the left argument $\chi_{a,(b)}$ and parameter `Fb` is the right argument $\chi_{b,(c)}$.

Thus, the example of Eq.(1), shown in Fig.1, could be written with the following source code:

```
ChMovingFrame<> cs_30, cs_32, cs_21, cs_10;
cs_10.coord.pos = ChVector<>(2,4,1);
...  etc ...
cs_30 = cs_32 >> cs_21 >> cs_10;
```

We also implemented the $(\cdot)^{-1}$ operation, with arity $\bar{\alpha} = 1$, by overloading the `!` C++ unary operator. This requires the in-place evaluation of Eq.(19-23). We choose the `!` symbol for readability reasons and because it has higher precedence than `>>` in C++ syntax, so parentheses are rarely needed.

Thank to the implementation of the inversion, it is possible, again in example of Fig.1, to obtain `cs_32` if other frames are known: we multiply both sides by `!cs_10` and `!cs_21`, and remembering that `cs_ij >> !cs_ij` will cancel by Theorems 1 and 2, we simply write

```
cs_32 = cs_30 >> !cs_10 >> !cs_21;
```

Note that the previous statement would require two inversions and two coordinate transformations, but a more efficient approach can be developed. In fact we can implement an *inverse transformation* operator, named `<<`, which requires fewer CPU operations:

```
cs_32 = cs_30 << cs_10 << cs_21;
```

For reasons of space, details about the implementation of the `<<` operator are not given; suffices to say that formulas are not much different from the ones in Eq.(19-23). Also, we remark that such `<<` operator is not associative (although, given that C++ compilers evaluates expressions from left to right if no parentheses are used, this is seldom an issue).

Additionally, thank to further specialized implementations of the `>>` operator, one can mix objects of `ChMovingFrame` and `ChFrame` in the same expression. In the same way, it is possible to trasform simple 3D vectors of class `ChVector` instead than entire frames, for example as in:

```
vect_0 = vect_2 >> cs_21 >> cs_10;
```

This last example shows the reason why we preferred to define the $\mathcal{T}$ algebra such that it concatenates kinematic transformations from left to right instead than from right to left: in fact, in case no parentheses are used and there are multiple operators with the same precedence, C++ compilers evaluate expressions by taking couple of operands from left to right and transforming them into temporary data, up to having a single result; hence when transforming simple vectors, as in the example above, the compiler ends always with a sequence of vector-by-frame products that are quickly computed, whereas if we had chosen an algebra where one has to write instead `vect_0 = cs_10 * cs_21 * vect_2` (for example), the compiler would translate it into a sequence of frame-by-frame products up to the last frame-by-vector product[2]. The result would be the same, but the performance would be much poorer because frame-by-frame products are much slower than frame-by-vector.

All classes are templated and metaprogrammed (Alexandrescu 2001), they can work with floating point in double or single precision.

We remark that we performed intense benchmarks and deep profiling of the code, to obtain the best trade-off between computational efficiency, ease of use and exploitation of OOP features (H. Sutter 2004).

Finally, we implemented serialization methods for all the classes discussed in this paper, so they can be converted from transient to persistent data schemes, and vice versa, in a platform independent way. This is useful for storing data on disk or on networks.

The libraries for the $\mathcal{T}$ algebra has been extensively used in our Chrono::Engine C++ library for multi body simulation (Tasora 2011)(Tasora, Silvestri & Righettini 2007)(Tasora & Anitescu 2011). After testing and profiling we got satisfying results in terms of clean code, ease of development and fast computation. Such a library has been successfully used in various engineering projects by many programmers and users.

5. Validation of syntax

Having agreed that the second subscript of an element represents the frame to whom the coordinates are expressed, when looking at the examples exposed in these pages one can see that, in order to make sense from a kinematical point of view, the subscripts of the elements in the expressions must be chained.

For instance, in $\chi_{3,(0)} = \chi_{3,(2)} \succ \chi_{2,(1)} \succ \chi_{1,(0)}$ it can be seen that the two operands share respectively the second subscript and the first subscript, and the result has the remaining two subscripts, respectively the first of the first operand, and the second of the

[2]For instance, using Denavit-Hartenberg matrices $M_{a,b}$ transforming rotations and positions from a to b, one would rather write in this order: $\mathbf{v}_0 = M_{1,0} M_{2,1} \mathbf{v}_2$.

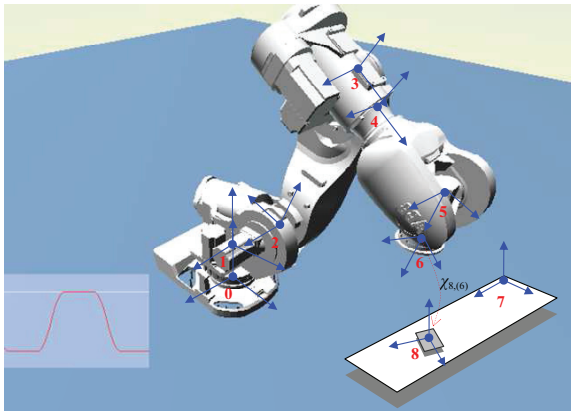

Figure 2: Example. Computing position, speed and acceleration of an item on a conveyor belt, respect to an end effector

second operand.

This fact can be exploited to implement an additional (and optional) layer, that takes care of validating if the programmer is writing transformations that make sense.

More in detail, one can point out the following, minimal, set of rules about the subscripts:

- $\chi_{c,(a)} = \chi_{c,(b)} \succ \chi_{b,(a)}$
  (the (b) subscript must match the b subscript, and the result gets the remaining two subscripts c and (a), in exact order).

- $\chi_{b,(a)} = \chi^{-1}_{a,(b)}$
  (the a and (b) subscripts are swapped to b and (a)).

To support this type of run-time validation, additional data can be added to each `ChMovingFrame` object, representing the two subscripts. When the `>>` operator or the `!` operator are used, the above mentioned rules are invoked and the correctness of the transformation is checked, so a warning, or an assert, or an exception-throwing can signal the problem. The data for the subscript can be a simple (unique) numeric identifier, or a mnemonic string, although the latter option would be slower in execution.

We remark that, by using template metaprogramming, the validation of the sequences of coordinate transformations could be also checked in compile-time, instead of run-time, and this would mean that there is no overhead on the execution time (although it is not as flexible, because objects cannot be reused with different bases once they are created).

Such optional possibility of validating the syntax of expressions for kinematic consistency is particularly useful for educational purposes.

6. Example

Figure 2 shows an example based on a 4-DOF industrial robot and a conveyor belt, both simulated with our multibody software. One must compute the position, speed and acceleration of an item on a conveyor belt respect to the end effector, assuming that position, speed and acceleration of the item (frame n.8) is known respect to the conveyor belt (frame n.7), and all frames of the parts of the robot are known respect to the previous joint, up to the base (frame n.0). By using the $\mathcal{T}$ algebra, one can obtain position, rotation, velocity, angular velocity, acceleration, angular acceleration of frame n.8 respect to frame n.6 using a single expression:

$$\begin{aligned}\chi_{8,(6)} =& \chi_{8,(7)} \succ \chi_{7,(0)} \succ \chi^{-1}_{1,(0)} \succ \chi^{-1}_{2,(1)} \\ & \succ \chi^{-1}_{3,(2)} \succ \chi^{-1}_{4,(3)} \succ \chi^{-1}_{5,(4)} \succ \chi^{-1}_{6,(5)}\end{aligned}$$

Equivalently, one could write instead:

$$\begin{aligned}\chi_{8,(6)} =& \chi_{8,(7)} \succ \chi_{7,(0)} \succ (\chi_{6,(5)} \succ \chi_{5,(4)} \\ & \succ \chi_{4,(3)} \succ \chi_{3,(2)} \succ \chi_{2,(1)} \succ \chi_{1,(0)})^{-1}\end{aligned}$$

that is, by doing the product of two groups of factors, also:

$$\chi_{8,(6)} = \chi_{8,(0)} \succ \chi^{-1}_{6,(0)} = \chi_{8,(0)} \succ \chi_{0,(6)}$$

7. Conclusion

This paper discusses the $\mathcal{T}(\mathbb{T}, \succ)$ algebra as a compact formal method to represent kinematic transformations in chains of moving frames. This formal framework maps well into a software implementation, thank to the operator-overloading capabilities of the C++ language.

Of course other methods already exist to perform kinematic computations, but most often they require separate expressions (and many lines of code) to get also speeds or accelerations, whereas the discussed method aims at compactness and readability; therefore in most cases even complex kinematic transformations can be written with a single line of C++ code.

Targeting multibody and physics simulations, this algebra is implemented in our open source library Chrono::Engine, that already found application in various engineering fields and is currently adopted in many research labs around the world.

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