We review the problem of a dimensional check as a language feature for most of the high-level programming languages and the possible solutions of this issue. We introduce our C++ library designed to make 2D and 3D vectorial operations using units of measurement. Eventually, we present our plans for future improvements of the current implementation.

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1. Introduction

Dimensional analysis is one of the most powerful tools available in physics to verify the correctness of mathematical formulas describing physical processes. However, this tool alone is not able to spot all possible mistakes, it allows only to perform a fast-check and to easily highlight the faulty operations and provide a consistence check for the whole process.

Nowadays, complex simulations and derivations are performed using computing algorithms taking advantage from high-speed calculation and numerical correctness due to the advances of computing technology. However, when using complex algorithms, spanning for thousands of source code lines divided in tens of files, we tend not to automatically trust the results or, much worse, to blindly accept them. Because there is no bug-free software implementation we have to mitigate the impact of possible errors using count-less checks in code and using proper testing procedures, which often are as time-consuming as the development itself. An appropriate approach is to use development techniques that could help reduce the overall cost of software development [1]. Due to historical reasons, most high-levels programming languages lacks of a dimensional check as a language feature, they work on floats and integers, leaving to the programmer mercy the responsibility to keep trace of their semantic meaning, leading to many potential mistakes.

Several libraries try to provide the dimensional analysis check at compile time or at run-time. However, as
shown by Mc.Keever [2], there is a clear reticence to use such solutions due to:

- Difficulty to use unfamiliar and complex libraries
- Fear to add external dependencies
- Concerns about the performance impact
- Possible limitations on using external libraries or complex data structures such as matrices and vectors.

In section 2 we review the existing solutions available in the most common programming languages, we will describe our proposed solution and concrete examples in section 3 and we present a performance analysis in section 4. Limitations of the current development and future plans for improvements are discussed in section 5 and eventually, conclusions are drawn.

2. Existing solutions

For a comprehensive review of dimensional analysis in programming languages we refer to [3]. Apple’s Swift [4] and F# [5] are two widespread programming languages that provide native support for UoM-aware (units of measure) quantities. Promoting UoM analysis to a language feature has the benefit of immediate access to meaningful error messages. Unfortunately, there are only a few programming languages that offer native support on this matter, most languages have an external library which relies on generic programming techniques.

The most popular solution for C++ is Boost.Units [6], which makes possible the UoM validation at compile time. Its main advantage is that it is included in the Boost framework, a comprehensive set of libraries which is used as launchpad for features that are later included in the standard library of the language. Unfortunately, Boost is quite often seen as a heavy dependency.

For the FORTRAN language there is the PHYSUNITS module [7] which provides support for dimensional-aware routine creation. While this solution is versatile, allowing working with both F77 and F90 code, because dimension information is carried alongside numerical values PHYSUNITS introduces a run-time execution overhead in term of speed and memory usage.

Dimensional analysis is not limited to compiled languages, Python supports run-time dimensional analysis check thanks to libraries like Pint [8].

Almost all the existing libraries do not provide native support for vectorial computation. However, there are two solutions in high energy physics (HEP) for vectorial operations: CLHEP [9] and Eigen [10]. They provide representations for both 2D and 3D vectorial quantities and n-dimensional matrices. However, none of them has built-in support for dimensional-aware units, relying on primitive numeric types available in C++.

3. Our UoM implementation

Integrating Boost.Units, Univec is our C++ library that allows 2D and 3D vectorial operations. We provide a tool for dimension-aware vector calculations which has a compile-time check of dimensional correctness.

The source code is available under open-source license https://gitlab.com/micrenda/univec.

Our implementation makes heavy use of generic template programming, shifting the cost of the dimensional check at compiling time, removing, in principle, any run-time overhead. The drawback is an increased usage complexity, which may discourage non-experienced C++ developers. We tried to mitigate this issue providing a set of default quantity alias, which covers the most common quantities used in physics. This allows easy-to-remember type names to define a variable, such as:

dfpe::QtySiVelocity my_var;

using a shorter name then its canonical name:

boost::units::quantity<boost::units::si::velocity> my_var;
The full list of aliases defined can be found at the address: https://gitlab.com/micrenda/qtydef

3.1. Usage examples

Using the library we developed, together with our custom type definitions, we can write compact and semantically clear code with fully benefit of dimensional-check at any instant. For example, to calculate the energy of an object, we can use the well-known formulas:

VectorC3D<QtySiVelocity> vec1;
vec1 = VectorC3D<QtySiVelocity> (23.5 * si::meter_per_second,
45.0 * si::meter_per_second,
63.0 * si::meter_per_second);
QtySiEnergy kinetic_energy =
1./2. * si::kilogram * vec1.normSquared();
cout << "Kinetic energy: " << kinetic_energy << endl;
QtySiLength height(3. * si::metre);
QtySiAcceleration g(9.8 * si::metre_per_second_squared);
QtySiEnergy gravitational_energy = mass * height * g;
cout << "Gravitational energy: " << gravitational_energy << endl;
QtySiVelocity c(299792458. * si::metre_per_second);
QtySiEnergy einstein_energy = mass * c * c;
cout << "Einstein’s energy: " << einstein_energy << endl;

however, if we perform any definition mistake, such as:

QtySiLength mass(1. * si::kilogram);
or a plain calculus error, like this one:

QtySiMass mass(1. * si::kilogram);
VectorC3D<QtySiVelocity> vec1 (23.5 * si::meter_per_second,
45.0 * si::meter_per_second,
63.0 * si::meter_per_second);
// This operation needs to include the module
// of the velocity vector squared
QtySiEnergy kinetic_energy = 1./2. * mass * (vec1 + vec1);
cout << "Kinetic energy: " << kinetic_energy << endl;

we will get a compilation error that will not allow to compile and use this code (as shown in listing [I]).

3.2. Reference frame transformations

While using UniVec, we found that formulas are simplified for coordinate transformation. One clear example comes from the simulation of microscopic electron-molecule non-relativistic interactions in the center-of-momentum reference frame. Any linear transformation can be represented by a transformation-matrix: complex transformations can then be easily represented and computed by chaining multiple simpler transformations such as translations, rotations and scaling operations.

One can make a frame transformation using a concrete implementation of the abstract class BaseFrameC3D (in table [I] we present ready-to-use implementations). One can transform any vector in and out the new reference frame:

VectorC3D<QtySiLength> translation (QtySiLength(), QtySiLength(1. * si::meter), QtySiLength());
TranslateFrameC3D<QtySiLength> frame(translation);
VectorC3D<QtySiLength> globalPosition; // ( 0, 0, 0) m
VectorC3D<QtySiLength> localPosition = frame.forward(globalPosition); // ( 0,-1, 0) m
localPosition += Vector(QtySiLength(1. * si::meter), QtySiLength(1. * si::meter), QtySiLength(1. * si::meter)); // ( 1, 0, 1) m
VectorC3D<QtySiLength> globalPosition = frame.backward(localPosition); // ( 1, 1, 1) m

Multiple transformations can be combined to describe complex scenarios, using the syntax:

VectorC3D<QtySiLength> translation; translation.y = quantity<si::length>(1. + si::meter);
EulerRotation3D<QtySiLength> rotation( QtySiPlaneAngle(45. * degree::degrees), QtySiPlaneAngle(), QtySiPlaneAngle(),
RotationMode::INTRINSIC, RotationAxis::X, RotationAxis::Y, RotationAxis::Z);
to notice that $\mathbf{u}$ represents a pure-scalar vector. The operations

\begin{align*}
\mathbf{u} + \mathbf{v} &= \mathbf{u} + \mathbf{v} + \mathbf{u} + \mathbf{v} \\
\mathbf{u} - \mathbf{v} &= \mathbf{u} - \mathbf{v} - \mathbf{u} - \mathbf{v} \\
\mathbf{u} \times \mathbf{v} &= \mathbf{u} \times \mathbf{v} \\
\mathbf{u} / \mathbf{v} &= \mathbf{u} / \mathbf{v} \\
\mathbf{u} \times \mathbf{k} &= \mathbf{u} \times \mathbf{k} \\
\mathbf{v} \times \mathbf{k} &= \mathbf{v} \times \mathbf{k} \\
\mathbf{u} \times \mathbf{v} &= \mathbf{u} \times \mathbf{v} \\
\mathbf{u} / \mathbf{k} &= \mathbf{u} / \mathbf{k} \\
\mathbf{u} + \mathbf{v} &= \mathbf{u} + \mathbf{v} \\
\mathbf{u} - \mathbf{v} &= \mathbf{u} - \mathbf{v} \\
\mathbf{u} \times \mathbf{v} &= \mathbf{u} \times \mathbf{v} \\
\mathbf{u} / \mathbf{v} &= \mathbf{u} / \mathbf{v} \\
\mathbf{u} \times \mathbf{k} &= \mathbf{u} \times \mathbf{k} \\
\mathbf{v} \times \mathbf{k} &= \mathbf{v} \times \mathbf{k} \\
\mathbf{u} \times \mathbf{v} &= \mathbf{u} \times \mathbf{v} \\
\mathbf{u} / \mathbf{k} &= \mathbf{u} / \mathbf{k} \\
\mathbf{u} + \mathbf{v} &= \mathbf{u} + \mathbf{v} \\
\mathbf{u} - \mathbf{v} &= \mathbf{u} - \mathbf{v} \\
\mathbf{u} \times \mathbf{v} &= \mathbf{u} \times \mathbf{v} \\
\mathbf{u} / \mathbf{v} &= \mathbf{u} / \mathbf{v} \\
\mathbf{u} \times \mathbf{k} &= \mathbf{u} \times \mathbf{k} \\
\mathbf{v} \times \mathbf{k} &= \mathbf{v} \times \mathbf{k} \\
\mathbf{u} \times \mathbf{v} &= \mathbf{u} \times \mathbf{v} \\
\mathbf{u} / \mathbf{k} &= \mathbf{u} / \mathbf{k}
\end{align*}

Table 2. List of operators implemented for each type of 2D, 3D-vector and operations. $u$ and $v$ symbols represents vector quantities while $k$ represents a pure-scalar vector. The operations $+,-,\ast$ and $\div$ represents the operator-assignment operators in C++. It is important to notice that $u \ast v$ and $u \div v$ does represent, respectively, element-wise multiplication and division, which is not equivalent to scalar or vector product (these operations can be performed using the dot and cross methods, instead).

Listing 1: Example of units mismatch between VectorC3D and scalar value. Parts of this error were omitted for readability.

| Class name         | Description                                      |
|--------------------|--------------------------------------------------|
| TranslateFrameC3D  | Linear translation by a compatible vector        |
| RotateFrameC3D     | Rotation according a Quaternion3D or an EulerRotation3D |
| ScaleFrameC3D      | Scaling by a scalar or by a different value for each axis |
| CompositeFrameC3D  | Wrap two transformation in a single one          |

Table 3. List of ready to use reference frame transformations, that can be used to describe complex frame transformations. The class CompositeFrameC3D is rarely used directly but can be created combining the other transformations using the >> operator.
4. Performance study

Our performance testing consists in comparing three types of methods for calculating the same operation. The first one is Raw, where the computation has no dimensional check, using only C++ primitive types such as `double`. For the second method Semi, we employ the Boost.Units method without the support of vectorial operation. The third method is Univec, where our library is performing UoM-aware vectorial operation. We aim to investigate the performance loss due to UoM framework.

In fig. 1 we see that while Semi and Univec are quite similar, there is a significant performance difference between Raw and both Semi and Univec. Raw has a mean run time of about a third of the other two.

We conclude that the performance loss is coming from the underlying UoM library Boost.Units and not from Univec.

The values shown in fig. 1 are averages obtained for 1000 runs with 10000 random vectors each for the following operations: Norm Squared, Norm, isNull, Dot Product and Cross Product for a 3D Vector.

5. Limitations and future plans

The use of Boost.Units as underlying library for Univec has several non-negligible weak points that, unfortunately, seem not to have a solution in the near future. The first limitation is that this library is available only as part of a more comprehensive framework, Boost, which is often seen by many software developers as a heavy dependency. The second limitation is that the current implementation is based on heavy use of Boost Metaprogramming Library (MPL) and of template meta-programming techniques, which makes the analysis of error messages (especially on GCC compiler) very hard to understand for non-experienced developers. In addition, despite the fact that this library is advertised as zero-overhead, but, as we can observe in fig. 1 that there is still a non-negligible performance cost for its usage, due to missing compiler optimizations.

There is a proposal to introduce the support for UoM-aware units directly in the standard language (see Mateusz Pusz’s talk at CppCon 2019 [11]). This approach will solve the problems presented above and will provide a more reliable solution with a less steep learning curve. We plan to switch our Univec implementation from Boost.Units to any standard library implementation, when it will become available.
6. Conclusions

In this paper we presented Univec, our solution for the issue of UoM-validation in software development, aiming to improve the heavy vectorial calculations.

After a brief overview of the existing UoM solutions, we discussed the limitations which make them unsuitable. We presented an user-case scenario of our solution and we have estimated the performance.

We plan to move to a native solution when an implementation of a UoM-aware library will be published in the C++ standard library.

The developing of this library started as an internal project during the designing phase of our Betaboltz [12] project. While working on this project, we found the benefits of integrating the UoM analysis directly in our source code, virtually removing the most usual causes of common mistakes. Even if this solution does not remove all the sources of errors, Univec allowed us to focus on the main workflow of the development, increasing the confidence on our implementation.

We hope that in the future similar solutions will be widely accepted in the development of software solutions for the scientific community.

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