The Impact of Precision Tuning on Embedded Systems Performance: A Case Study on Field-Oriented Control

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Approximate Computing

Precision Tuning:

Lowering a computational kernel's precision to achieve

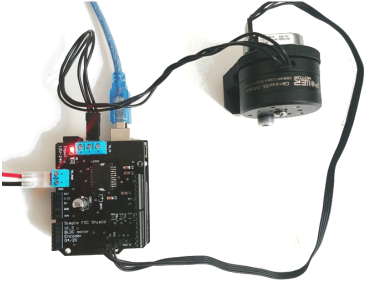
- lower execution time
- decreased power consumption

Accomplished through:

- low precision floating-point formats (e.g., bfloat16)
- **fixed-point arithmetic**
- ...

A case study: Field-Oriented Control

Control of electrical motor drives



Typical use-case of microcontroller-based embedded systems

Field-Oriented Control

Targets induction or permanent magnet synchronous motors

Pro smooth operation over the full speed range

Pro high dynamic performance (fast acc/deceleration)

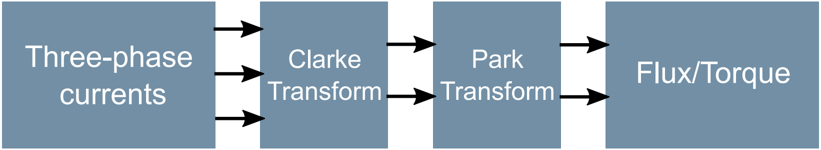
Pro high power efficiency

Con high computational cost

Applications:

- high-power electric propulsion systems in trains and cars (General Motors EV1 and Tesla Model S)
- drones
- generators for wind turbines

Field-Oriented Control



Clarke Transform

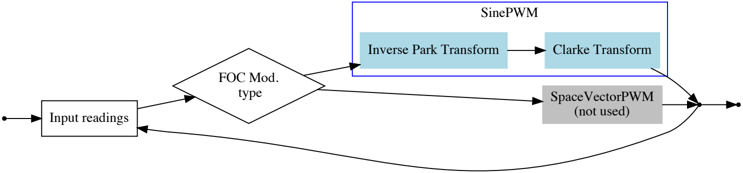
$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ \frac{1}{\sqrt{3}} & \frac{2}{\sqrt{3}} & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

Park Transform

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

FOC Miniapp

Arduino SimpleFOClibrary*



*https://github.com/simplefoc/Arduino-FOC

Dynamic Fixed Point and TAFFO

TUNING ASSISTANT FOR FLOATING POINT TO FIXED POINT OPTIMIZATION*

Dynamic Fixed Point:

Changing bit partitioning during the execution to improve precision while mantaining the benefits of using fixed point

*Stefano Cherubin et al. "TAFFO: Tuning Assistant for Floating to Fixed point Optimization". In: *IEEE Embedded Syst. Lett.* 12.1 (2019), pp. 5–8. ISSN: 1943-0663. DOI: 10.1109/LES.2019.2913774.

TAFFO and math functions

Function generator based on CORDIC (FixM*)

Classic iterative algorithm

- Low code size
- Fast convergence
- Good precision

*Daniele Cattaneo et al. “FixM: Code generation of fixed point mathematical functions”. In: *Sustainable Computing: Informatics and Systems* 29 (2021), p. 100478. ISSN: 2210-5379. DOI: 10.1016/j.suscom.2020.100478.

TAFFO and math functions

Look-Up Tables

Compute function for all input values at compile time

- Code size can get huge
- Very fast at runtime
  (single memory lookup after range reduction)
- Precision depends on spacing between inputs
  (trade-off with code size)

Can use trigonometric properties for lower code-size.

Experimental Evaluation

We evaluate:

- execution time $\rightarrow$ energy consumption
- computation accuracy
- code size

Hardware Setup

F2 STM3220G-EVAL, ARM Cortex-M3@120 MHz, 128 kB RAM, **No HW FP support**

F4 STM32F4-Discovery, ARM Cortex-M4@168 MHz, 192 kB RAM, **HW FP support**

Software Setup

Arduino *SimpleFOCLibrary* optimized with TAFFO in 4 configs:

ID	1^{st} call	2^{st} call
C2	CORDIC	CORDIC
L1C1	LUT	CORDIC
C1L1	CORDIC	LUT
L2	LUT	LUT

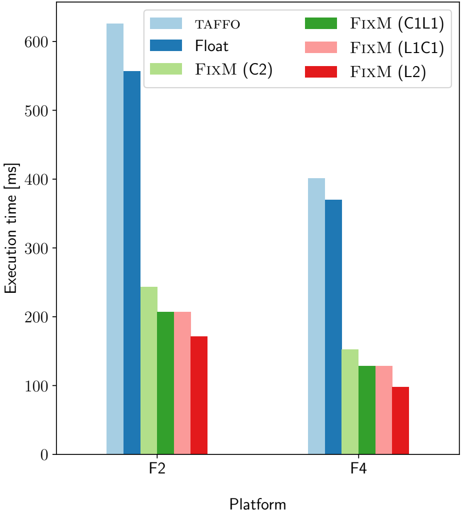
Software Setup

Baselines:

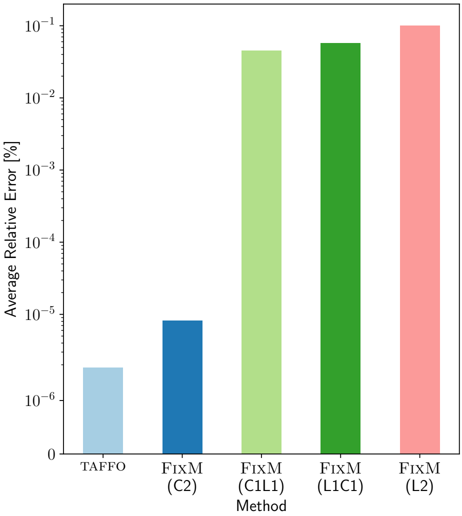
- GCC-based STM compiler (floating-point) + *newlib*[*] v. 2.5.0
- LLVM+TAFFO fixed-point (but floating-point *newlib*)

[*] https://sourceware.org/newlib/

Execution Time



Accuracy

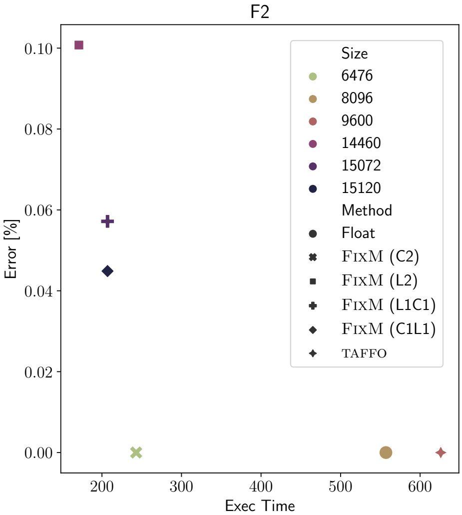


Average Relative Error [%]
10^−1
10^−2
10^−3
10^−4
10^−5
10^−6
0
TAFFO
FixM (C2)
FixM (C1L1)
FixM (L1C1)
FixM (L2)
Method

Code Size

		F2	
	All Code	Appl. Code	Constants
Float	7424	1892	672
TAFFO	8912	832	688
C2	6000	2538	476
L1C1	6404	2204	8668
C1L1	6452	2158	8668
L2	6048	1804	8412

Design Space



Conclusion

Impact of precision tuning on FOC:

- speedup up to 278%
- error $\leq 0.1\%$
- reduced code size (trade-off)

Future developments:

- Support more math functions (for now only `sin`/`cos`)
- More numerical formats (logarithmic, Posit)
- Library of domain-specific miniapps

Thank you for your attention.

Bibliography I

Cattaneo, Daniele et al. "FixM: Code generation of fixed point mathematical functions". In: *Sustainable Computing: Informatics and Systems* 29 (2021), p. 100478. ISSN: 2210-5379. DOI: 10.1016/j.suscom.2020.100478.

Cherubin, Stefano et al. "TAFFO: Tuning Assistant for Floating to Fixed point Optimization". In: *IEEE Embedded Syst. Lett.* 12.1 (2019), pp. 5–8. ISSN: 1943-0663. DOI: 10.1109/LES.2019.2913774.