（様式４）

二国間交流事業 共同研究報告書

令和５年４月 14 日

独立行政法人日本学術振興会理事長　殿

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1. 事　業　名　相手国：フランス　（振興会対応機関：Inria　）との共同研究

2. 研究課題名

（和文）ロボットの検証のための解析ライブラリの形式化

（英文）Formal Library of Analysis for the Verification of Robots

3. 共同研究実施期間　2020 年 4 月 1 日 ～ 2023 年 3 月 31 日（ 3 年 0 ヶ月）

【延長前】　年　月　日 ～　年　月　日（　年　ヶ月）

4. 相手国側代表者（所属機関名・職名・氏名【全て英文】）

Inria (Institut National de Recherche en Informatique et en Automatique)・Senior researcher・BERTOT Yves

5. 委託費総額（返還額を除く）

本事業により執行した委託費総額		3,533,050　円
内訳	1年度目執行経費	0　円
	2年度目執行経費	1,811,650　円
	3年度目執行経費	1,721,400　円

6. 共同研究実施期間を通じた参加者数（代表者を含む）

日本側参加者等	5 名
相手国側参加者等	7 名

＊ 参加者リスト（様式 B1(1)）に表示される合計数を転記してください（途中で不参加となった方も含め、全ての期間で参加した通算の参加者数となります）。

7. 派遣・受入実績

	派遣		受入
	相手国	第三国	
1 年度目	0	0	（ ）
2 年度目	3	0	（ ）
3 年度目	4	0	（ ）

＊派遣・受入実績（様式 B1(3)）に表示される合計数を転記してください。
派遣：委託費を使用した日本側参加者等の相手国及び相手国以外への渡航実績（延べ人数）。
受入：相手国側参加者等の来日実績（延べ人数）。カッコ内は委託費で滞在費等を負担した内数。

8. 研究交流の概要・成果等
(1)研究交流概要（全期間を通じた研究交流の目的・実施状況）

The goal of this project is the application of higher-order logic proof systems to the safety of cyber-physical systems. Our research activities focused on the formalization of the mathematical foundations necessary for the verification of automated systems and on the development of software tooling to extract executable code from formal specifications. We aimed at an application to a robot moving on a two-dimensional surface. During this project, we organized every year at least two half-day meetings to which all participants attended with scientific presentations (online meetings during the pandemic and face-to-face meetings in Sophia Antipolis after travel restrictions were lifted). We also organized several online meetings with members of the project and external participants (one coding sprint, regular MathComp-Analysis meetings, etc.). We moreover held several development meetings (online during the pandemic and in Sophia Antipolis after the pandemic). As a result of our research activities, we have been able (1) to develop a formal foundation for real analysis that is also used by other researchers and a formal foundation for motion planning and trajectories that can be used to specify 2D trajectories for robots and reason about collisions with obstacles, (2) to develop new tools to extract executable code from/to the Coq proof assistant, and (3) to communicate by means of joint publications and presentations in academic venues.

(2)学術的価値（本研究交流により得られた新たな知見や概念の展開等、学術的成果）

We developed as open source software formal libraries for real analysis (MathComp-Analysis, https://github.com/math-comp/analysis) and for motion planning and trajectories (https://github.com/math-comp/trajectories), as well as extensions to extract code from/to the Coq proof assistant (https://github.com/akr/codegen). We also contributed to the improvement of existing formal libraries, most notably Inria/Microsoft's Mathematical Components (MathComp) and AIST/Nagoya University's libraries on convexity, finite probabilities, and category theory (Infotheo, https://github.com/affeldt-aist/infotheo; Monae,) and category theory (Monae, https://github.com/affeldt-aist/monae). This work contributed to 12 publications and presentations in international venues (see the accompanying list of research results (【B1(4)】研究発表)).

(3)相手国との交流（両国の研究者が協力して学術交流することによって得られた成果）

The collaboration between the France and the Japan sides was instrumental to the development of the formal libraries listed in (2). For example, the improvement of Infotheo and Monae on Japan side relies on Inria's Hierarchy-Builder tool that members learned during the coding sprint organized during the second year of this project. The development of the library on motion planning and trajectories relies on Infotheo developed on the Japan side and on MathComp-Analysis which is a collaborative development. The development of MathComp-Analysis is a collaborative effort, see for example its formalization of exponential, logarithm, and trigonometric functions, or its formalization of Lebesgue measure and integral. The accompanying list of research results (【B1(4)】研究発表) includes 5 pieces of work co-authored by participants from both sides.

(4)社会的貢献（社会の基盤となる文化の継承と発展、社会生活の質の改善、現代的諸問題の克服と解決に資する等の社会的貢献はどのようにあったか）

Formal verification is one way to address the safety concerns raised by the application of robotics to human activities. Such applications are bound to grow in numbers. In Japan, for example, we expect robotics to address soon social issues such as the aging society or labor shortage. In the future, formal verification will turn into a requirement for robots, like it is already the case with information technology (through standards like Common Criteria). Our work is a first step in this direction. We also expect the formal libraries resulting from our project to be reusable so as to decrease in the future the cost of formal verification of other applications such as autonomous vehicles in general.

(5)若手研究者養成への貢献（若手研究者養成への取組、成果）

Several graduate students were involved in our research activities. Kazuhiko Sakaguchi is a PhD Candidate at the University of Tsukuba and his PhD thesis will feature work partly developed during the course of this project. Takafumi Saikawa defended his PhD during the first year of this project using work partly developed for this project; he continued his research during this project as a researcher. Quentin Vermande is now a PhD candidate under the supervision of Yves Bertot: as a graduate student, he used work from this project on the formalization of convexity for his Master thesis and contributed with several improvements to the libraries MathComp, MahtComp-Analysis, Infotheo, and the formalization of trajectories.

(6)将来発展可能性（本事業を実施したことにより、今後どの様な発展の可能性が認められるか）

The formalization effort of functional analysis and of motion planning and trajectories continues as a collaborative effort with most members of this project. At least two joint papers are under submission for publication. Some project members are currently considering application to a new bilateral research project to deepen and broaden collaboration.

(7)その他（上記(2)～(6)以外に得られた成果があれば記載してください）
例：大学間協定の締結、他事業への展開、受賞など

N.A.