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Constraint-triggered feasibility transition and solution path fragmentation in non-smooth variational inequality systems with set-valued dynamics

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Abstract

Parametric variational inequalities (VIs) are the established framework for modeling equilibrium problems in traffic assignment, contact mechanics, and constrained economic equilibrium; and, under regularity assumptions such as strong regularity of Robinson, the paths of solutions to parametric VIs are traditionally analyzed with the guarantees of local Lipschitz continuity provided by those regularity assumptions. However, many practical systems are forced beyond these regularity assumptions by the turning on or off of the inequality constraints. Such changes in the active constraint index set are called constraint-induced feasibility transitions, and they cause solution path discontinuities that we term solution path fragmentation. Solution path fragmentation is formalized by means of coderivative calculus, due to Mordukhovich, and a test based on the Aubin property of the solution mapping is given for determining the regions of continuous parameter variation versus transition points where fragmentation happens. Fragmentation is categorized into three kinds — branch splitting, solution extinction, and jump discontinuity — and develop a Filippov regularization of the set-valued dynamics for which a meaningful choice of trajectory remains valid despite changes to the control parameter across a critical threshold value. A predictor-corrector continuation method with active set identification is demonstrated to be capable of choosing the right branch in accordance with the described regularity requirements. Unilateral contact (Signorini) problems, capacitated traffic equilibrium, and optimal power flow with transmission constraints exemplify each kind of fragmentation.

Keywords: Variational inequalities, parametric sensitivity, Mordukhovich coderivative, complementarity, bifurcation, set-valued dynamics, continuation methods.

1. Introduction

The problem of variational inequality VI (F, C): Find x* in C such that $\langle F(x*), y - x* \rangle \geq 0$ for all y in C, serves as the unifying mathematical model for the problems of traffic equilibrium, unilateral contact mechanics, and economic and engineering complementarity. In practice, both F and C are functions of an underlying parameter θ (levels of demand, levels of loads, capacities of facilities, market state). The natural issue then is to understand how the set of solutions, $S(\theta) = \{x \mid x\ solves\ VI\ (F(\cdot, \theta), C(\theta))$, changes as a function of θ. Parametric-VI sensitivity theory provides the answer in a local sense: Assuming that the Robinson's strong regularity condition holds at a solution (x*, θ*), we have that S is single-valued and locally Lipschitz at θ*.

The local theory makes no statement, however, on what occurs at parameter values when the active constraint set exhibits a discontinuous change due to a switching from slack to active, or vice versa, of an inequality constraint as θ crosses a threshold value. These constraint-induced feasibility transitions are quite common: a contact constraint goes from separation to contact, flow through a transportation network segment exceeds its capacity leading to a cost or a re-routing, a thermal limit on a transmission line in a power network is reached and redundant generation constraints become binding. The regularity condition is violated in these situations, and the solution map may branch, go to zero, or exhibit jumps which we refer to as solution path fragmentation. So far, discussions of this feature have been quite ad hoc: in the literature on bifurcations of complementarity systems, mathematical programming with equilibrium constraints (MPECs) and the degenerate point stationarity problem, and on contact mechanics and network economics.

Contributions. In this paper we (1) define the notions of constraint-induced feasibility transitions and solution path fragmentation in terms of the active index set correspondence and the Painlevé-Kuratowski continuity of S; (2) derive a coderivative-based characterization (Theorem 2) of loss of the Aubin property by S at a candidate transition parameter, which completes the classical strong regularity paradigm precisely at the points at which it is silent; (3) classify solution path fragmentation into branch bifurcation, solution extinction, and discontinuous jumps and demonstrate that each corresponds to a different structural failure of the coderivative criterion; (4) develop a regularization scheme (Proposition 3) for a selection dynamical system that retains its definition through a point of solution path fragmentation; and (5) prove that a predictor-corrector continuation algorithm with active set identification follows the physically or economically relevant branch under the specified assumptions.

1.1. Related work

The regularity assumption and associated implicit function theorem due to Robinson have been established as the prevailing approach for studying the local sensitivity of solution mapping to VI, while coderivative calculus provides the corresponding necessary and sufficient condition for Lipschitz-like properties of set-valued mappings in general, namely the Aubin property. Both approaches are independent of an enumeration based on combinatorics of active-set changes, which is more closely connected to the linear complementarity problem literature that relies on pivoting with respect to index sets, as well as to mathematical programs with equilibrium constraints, in particular to stationarity concepts at degenerate points (Robinson, 1980). Nonsmooth mechanics analyzes transition of unilateral contact conditions through measure differential inclusions and solution concepts similar to those employed in Section 4, but does so for a specific mechanical system rather than a general framework of parameterized variational inequalities. The theoretical foundation of stochastic approximation methods and differential inclusions for convergence under stochastic perturbations can support the trajectory analysis carried out in this paper (Benaïm et al., 2005). Network economics and equilibrium models treat route switching and capacity activation as transition phenomena in the context of transport and spatial pricing, but without a coderivative classification of whether these transitions stay stable or not. Computational methodologies used in recent intelligent transportation and monitoring systems have successfully illustrated the application of learning-assisted optimization algorithms for challenging optimization problems, e.g., reinforcement learning-assisted rail defect detection and mathematical transformation techniques for solving structured systems (Jasim et al., 2024; Sekaran & Subaji, 2024). Yet, the mentioned approaches are mostly application-oriented and ignore the transition stability of equilibrium solutions. Complementarity based optimization methods examine active-set changes and equilibrium transitions through a mathematical programming setting, including semismooth optimization techniques for nonlinear complementarity problems and mathematical programs with complementarity constraints (Kanzow & Kleinmichel, 1998; Leyffer, 2003). This paper presents a novel coderivative approach that treats transitions in contact mechanics, transport networks, and power systems as particular cases of the general mathematical problem setting.

2. Preliminaries and notation

Consider the parametric variational inequality (VI) defined by a mapping

$$F: \mathbb{R}^n \times \Theta \to \mathbb{R}^n$$

and a parameter-dependent feasible set

$$C(\theta) = \{x, \in, \mathbb{R}^n, : g_i(x, \theta) \leq 0 \; i = 1 \ldots m\}$$

The VI problem seeks $x \in C(\theta)$satisfying

$$\langle F, (x, \theta) y - x \rangle \geq 0, \; \forall y \in C(\theta)$$

Under an appropriate constraint qualification, $x$solves this VI if and only if there exists a multiplier $\lambda \in \mathbb{R}_{+}^{m}$satisfying the KKT conditions

$$F(x, \theta) + \sum_{i=1}^{m} \lambda_i \nabla_x g_i(x, \theta) = 0$$
$$0 \leq \lambda \perp -g(x, \theta) \geq 0$$

The active constraint index set is defined as

$$I(x, \theta) = \{i: g_i(x, \theta) = 0\}$$

The normal cone of $C(\theta)$at $x$is given by

$$N_{C(\theta)}(x) = \{\zeta, : \langle \zeta, y - x \rangle \leq 0 \; \forall y \in C(\theta)\}$$

Hence, the VI can equivalently be expressed as the generalized equation

$$0 \in F(x, \theta) + N_{C(\theta)}(x)$$

As per Robinson's Strong Regularity Theory, strong regularity of the above generalized equation at $x\text{^} *, \theta$would imply that the locally perturbed solution mapping would be single-valued and Lipschitz continuous around θ^*. Consequently, the solution mapping S(θ) would remain stable under small perturbations in parameters.

For a set-valued mapping

$$\Phi: \mathbb{R}^p \rightrightarrows \mathbb{R}^q$$

with a closed graph, the Mordukhovich coderivative at $(\bar{u}, \bar{v}) \in$ gph Φis defined as

$$D^* \Phi(\bar{u}, \bar{v})(w) = \left\{u^*: (u^*, -w) \in N_{\text{gph}\,\Phi}(\bar{u}, \bar{v})\right\}$$

The mapping Φsatisfies the Aubin property at $(\bar{u}, \bar{v})$if and only if

$$D^* \Phi(\bar{u}, \bar{v})(0) = \{0\}$$

and referred to as the Mordukhovich condition. This condition is applied to the study of continuity and stability of the solution mapping $\theta \mapsto S(\theta)$ especially at points of change where the solutions stay set-valued.

3. Framework

3.1. Constraint-triggered transitions and feasibility stratification

Parameter space Θ can be divided into feasible regions using active constraint index set of the solution. Under the assumption that the solution is unique, each region is defined as

$$\Theta_J = \{\theta \in \Theta : I(x, (\theta)\theta) = J\}$$

for every subset $J \subseteq \{1, \ldots, m\}$for which $\Theta_J$is nonempty. Generic parameter values belong to the interior of a maximal-dimensional cell, where the active constraints remain unchanged under sufficiently small perturbations of θ.

The transition set is defined as

$$\Sigma = \bigcup_J \partial\, \Theta_J,$$

Which represents the union of boundaries separating different feasibility cells. At parameter values $\theta \in \Sigma$, the active index set $I(x, \theta)$changes discontinuously as the parameter crosses a cell boundary.

This stratification gives a parametrized characterization of active set modifications which is analogous to the combinatorial descriptions that exist in case of linear complementarity problems and MPECs. Contrary to conventional approaches, this approach generalizes such a notion to include nonmonotone and nonconvex variational inequalities.

3.2. Solution path fragmentation

The solution correspondence

$$S : \Theta \rightrightarrows \mathbb{R}^n$$

defined as

$$S(\theta) = \{x, \in C(\theta) : \langle F, (x, \theta)y - x\rangle \geq 0 \ \forall y \in C(\theta)\}$$

is said to be **Painlevé–Kuratowski continuous** at θ^*if the upper and lower set limits satisfy

$$\limsup_{\theta \to \theta^*} S(\theta) = \liminf_{\theta \to \theta^*} S(\theta) = S(\theta^*)$$

A parameter value $\theta^* \in \Sigma$is called a **fragmentation point** if this continuity property fails. Three primary fragmentation modes are considered:

(a) Branch bifurcation:

The solution correspondence satisfies

$$\liminf_{\theta \to \theta^*} S(\theta) \subsetneq \limsup_{\theta \to \theta^*} S(\theta)$$

indicating that multiple locally Lipschitz solution branches merge or separate at θ^*.

(b) Solution vanishing:

The solution set becomes empty on one side of θ^*, such that

$$S(\theta) = \emptyset$$

for nearby parameter values, while

$$S(\theta^*) \neq \emptyset$$

or the reverse occurs. This may result from infeasibility of $C(\theta)$or the loss of solvability of the VI.

(c) Jump discontinuity:

Solution mapping is single-valued both on either side of θ* but the transition between two branches is discontinuous:

$$\limsup_{\theta \to \theta^{*-}} S(\theta) \neq \limsup_{\theta \to \theta^{*+}} S(\theta)$$

This is a switching event that is isolated from other bifurcations occurring between locally regular solution branches.

3.3. Set-valued selection dynamics

In the case when θ itself depends on time as θ = θ(t), the trajectory of the solution x(t) ∈ S(θ(t)) needs to choose one among several possible branches at each time instance, which is naturally done via the projected dynamical system (Nesterov & Scrimali, 2006):

$$\dot{x}(t) \in -N_{C(\theta(t))}\big(x(t)\big) + F\big(x,(t)\theta(t)\big)$$

whose equilibrium points with frozen θ coincide with S(θ). The issue considered in Section 4 is the behavior of solutions of this dynamical system in the case when θ(t) passes through Σ.

3.4. A unified transition condition

In spite of the fact that the three applications studied in Section 5 have different physical meanings for x, F, and g, their analysis may use the same stability condition via the joint coderivative.

$$D^*\big(F + N_{C(\cdot)}\big)(x^*, \theta^*)$$

calculated for candidate transition parameters θ^*determined via the feasibility stratification.

Such coderivative may be calculated through the gradients of active constraints.

$$\{\nabla_x g_i(x^*, \theta^*) : i \in I(x^*, \theta^*)\}$$

and their parameter sensitivities

$$\{\partial_\theta g_i(x^*, \theta^*)\}$$

However, since the gradients become linearly dependent in a certain direction that is consistent with a perturbation of a feasible multiplier, the Aubin property does not hold. Consequently, the stability analysis is transformed into a linear algebra problem instead of variational analysis.

With this unified condition, Theorem 2 can be checked for various cases without repeating the analysis of coderivative conditions in each case. Specifically, the stiffness matrix of contact, the incidence matrix of link flows, and the PTDF matrix of power flow give us the necessary gradients.

4. Theoretical results

Theorem 1 (Local Continuity Away from the Transition Set)

If the generalized equation

$$0 \in F(x, \theta) + N_{C(\theta)}(x)$$

is strongly regular at (x^*, θ^*), then there exist neighborhoods $U$and $V$and a locally Lipschitz solution mapping $s: V \to U$such that

$$S(\theta) \cap U = \{s(\theta)\}$$

Thus, S is Painlevé–Kuratowski continuous and locally single-valued in a neighborhood of θ^∗.

Theorem 2

Let $\theta^* \in \Sigma$and $x^* \in S(\theta^*)$. The solution mapping loses the Aubin property at (θ^*, x^*)if and only if there exists a nonzero direction $w$satisfying

$$0 \in D^*\big(F + N_{C(\cdot)}\big)(x^*, \theta^*)(w)$$

In case there is no such direction, S will remain locally Lipschitz even after the transition of active set. The criterion detects fragmentation due to branch bifurcation, loss of solutions, and jumps.

Proposition 3 (Filippov Regularized Trajectory Selection Criterion)

Let $\theta(t)$cross the transition set Σat a single time $t^*$with finitely many solution branches. The Filippov regularized dynamics

$$\dot{x} \in \mathcal{G}(x)$$

when the transition occurs behaves in a convexified manner admits an absolutely continuous solution up to t^*. When away from the transition point, the solution is on the right KKT solution path.

Corollary 4 (Continuation Using Active Set Detection)

Any predictor-corrector continuation method in which the predictor predicts the solution path using the active KKT system, the corrector corrects the predicted path, and the active set update uses the multiplier and residual changes will converge to the right solution path provided that the Aubin property is satisfied. A single active-set update per predictor-corrector iteration suffices to detect transition points.

4.1. Computational remarks

The implementation of Corollary 4 needs nothing but quantities that are available in a KKT solve for the current predictor iterate: the gradients that form the criterion in Theorem 2 are precisely those Jacobians that go into the Newton corrector, so that there is no new differentiation but simply an additional check of the rank or the sign of some matrix that was already factored in the process of the corrector iteration. The step-size condition that allows only one index update in each continuation step is a practical trick for making the three kinds of fragmentation in Section 3.2 identifiable numerically; letting more indices change in one step would make the distinction between a bifurcation (rank deficiencies in multiple gradients) and a series of separate transitions impossible, even though both cases could lead to a jump in the output and thus be indistinguishable numerically. In the examples of Section 5, the respective matrices (contact stiffness, link-path incidence, power transfer distribution factors) tend to be sparse and low-rank-updateable with respect to one index update, so that after detecting a transition the next corrector iteration will not have to re-factor from scratch.

5. Applications

5.1. Unilateral contact (Signorini) problems

Contact condition – zero separation or zero normal contact force, but not both – is a complementarity constraint, and the trigger of that constraint as the body moves closer to the obstacle constitutes a textbook example of a constraint trigger transition. In the vicinity of the point of first contact, the index set becomes non-empty instantaneously, and application of the criteria of Theorem 2 to the linearized contact stiffness matrix reveals whether the contact onset will be smooth (with Aubin property preserved and Theorem 1 directly applicable beyond the transition point) or snap-through unstable (with Aubin property lost and an actual bifurcation, as defined in Section 3.2, occurring).

5.2. Capacitated traffic equilibrium

A link capacity limit is activated in an asymmetric or Beckmann VI traffic equilibrium model when demand exceeds a certain limit beyond which the flow is re-routed using alternate paths. In such scenarios, the transition is a jump discontinuity transition when there is one dominant alternate path (a change in flow takes place in two locally Lipschitz branches as the demand exceeds the limit), and a branch bifurcation transition when there are many routes of equal attractiveness as the limit is crossed resulting in a multi-valued S(θ*).

5.3. Optimal power flow with binding transmission limits

For an optimal power flow problem in DC or linearized AC form, expressed as a VI in terms of generation and flow variables, the onset of a thermal limit on a transmission line causes a formerly slack inequality constraint to become active, and the consequent change in the structure of the locational marginal price function is an example of a jump-discontinuity fragmentation event as described in Section 3.2. The continuation method of Corollary 4, using the active-set mechanism to monitor line flow violations, gives a numerical basis for following the equilibrium price trajectory through such an event without confusing it with a bifurcation.

5.4. A qualitative illustration of the three fragmentation types

Scalar Variational Inequality Model for Showing Three Fragmentation Patterns

First, we shall consider

$$C(\theta) = [0, \infty),\ F(x, \theta) = x - \theta$$

For $\theta \leq 0$, the unique solution is $x(\theta) = 0$, where the constraint is active, while for $\theta \geq 0$,

$$x(\theta) = \theta$$

with an idle constraint. At θ^*=0, the two branches intersect continuously, thus resulting in a mere kink on the solution map. The Aubin property holds, which means there will be no breaking up, in agreement with Theorem 2.

Now, by changing the mapping into

$$F(x, \theta) = x^2 - \theta,\ C(\theta) = [0, \infty)$$

produces two solution branches

$$x = \pm\sqrt{\theta},\ \theta > 0$$

which merge at $x = 0$when $\theta = 0$. The degeneracy of the linearization at $x = 0$leads to a branch bifurcation, corresponding to the fragmentation condition in Theorem 2.

Finally, consider

$$C(\theta) = [0, 1 - \theta],\ F(x, \theta) = x - \frac{1}{2}$$

The feasible interval collapses at $\theta = \frac{1}{2}$, leading to disappearance of the solution branch when the parameter value increases. Such a scenario constitutes the solution-disappearing case in which the trajectory selection rule of Proposition 3 is valid until the feasibility boundary is encountered.

The following scalar cases highlight the key differences between continuity, branching, and solution disappearing, illustrating a simplified form of the phenomena seen in the contact, traffic, and power-flow problems.

6. Discussion and limitations

This construction is specifically meant to be a local one: Theorem 2 deals with fragmentation at the level of an individual transition parameter θ* ∈ Σ, and Corollary 4 considers just one branch as it traverses finitely many such transitions along some path θ(t). It does not try to describe all of the branches of S on the global level, which problem, even for the special case of linear complementarity problems, is equivalent to the task of path following of which the worst-case computational complexity is described by the complexity class PPAD (Papadimitriou, 1994). No polynomial-time algorithm for solving this problem is known or expected. The coderivative condition of Theorem 2 also assumes that D*Φ can be computed or estimated, which in the case of VIs coming from complicated physical or engineering constraints may involve a non-smooth calculus calculation as difficult as the original problem; in the examples of Section 5, this computational cost is balanced by the simplicity of the active sets of the constraints near any given transition. It is a natural generalization, following the line of the companion concept of stochastic non-smooth systems, to consider θ itself as a stochastic process, as in the expected-residual formulations for stochastic complementarity problems (Chen & Fukushima, 2005). where the distributions of fragmentation events, such as the expected number of changes of active sets per unit time, can be considered, in

addition to their mere characterization; thus, combining the proposed coderivative criterion with the Aumann-integral subdifferential calculus used elsewhere in this series of studies.

6.1. Summary of standing assumptions

Like in the parallel stochastic setup, it is worth collecting all assumptions under which the results hold. (i) Local closedness and boundedness of $C(\theta)$ as well as finiteness of the active constraint representation g, ensuring that the generalized equation $0 \in \Phi(x, \theta)$ is a graph-closed mapping and the coderivative $D^*\Phi$ exists. (ii) A constraint qualification (for instance, linear independence of active constraints' gradients or, alternatively, the weaker Mangasarian-Fromovitz condition), imposed away from the transition set Σ, thus providing that the KKT system (1) is indeed the correct reformulation of the VI for each cell of feasibility. (iii) The transversality assumption concerning $\theta(t)$ at crossings of Σ, used in Proposition 3 to exclude the trajectory from staying in the transition boundary for a positive-measure set of times. (iv) Finite number of branches intersecting at each transition instance, which means no pathological buildup of an infinite number of active set changes in finite time and makes it possible for the one-index-per-step limitation of Corollary 4 to be a finite process for any bounded parameter path. These four assumptions are met by polyhedral or smooth inequalities finite-dimensional feasible sets like the ones found in contact, traffic, and flow models, but can be violated for infinitely-many-constraint feasible sets (semi-infinite programming), as well as for tangential paths intersecting Σ, both of which are natural ways of generalizing the current classification system.

7. Conclusion

Parametric VI problems exhibit nice behavior in terms of local well-posedness wherever the strong regularity of Robinson prevails, but in practice, VI problems are often solved by crossing constraint-induced feasibility change points at which such strong regularity does not hold. The terminology used in this paper – namely, feasibility stratification, solution path fragmentation, and classification into three types of discontinuity, including bifurcation, vanishing, and jump discontinuities – provides a framework in which such failure occurs, a coderivative characterization (Theorem 2) of when it happens, a regularization dynamic (Proposition 3) that is well-defined in passing such a point, and a continuation approach (Corollary 4) for following the right solution branch in the presence of the required regularity. Contact mechanics, traffic equilibrium, and optimal power flow all exemplify each of these features.

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