NECESSARY OPTIMALITY CONDITIONS FOR INFINITE HORIZON VARIATIONAL PROBLEMS ON TIME SCALES

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To George Leitmann on the occasion of his 87th birthday.

Abstract. We prove Euler–Lagrange type equations and transversality conditions for generalized infinite horizon problems of the calculus of variations on time scales. Here the Lagrangian depends on the independent variable, an unknown function and its nabla derivative, as well as a nabla indefinite integral that depends on the unknown function.

1. Introduction. In recent years, it has been shown that the behavior of many systems is described more accurately using dynamic equations on a time scale or a measure chain [1, 2, 8]. If the variational principle holds as a unified law [5], then the above time scale differential equations must also come from minimization of some delta or nabla functional with a Lagrangian containing delta or nabla derivative terms [7, 10, 12]. Here we consider the following infinite horizon variational problem:

\[ J(x) = \int_a^\infty L(t, x^\sigma(t), x_\nabla(t), z(t)) \nabla t \rightarrow \text{extr}, \tag{1} \]

where “extr” means “minimize” or “maximize”. The variable \( z(t) \) is defined by

\[ z(t) = \int_a^t g(\tau, x^\sigma(\tau), x_\nabla(\tau)) \nabla \tau. \]

Integral (1) does not necessarily converge, being possible to diverge to plus or minus infinity or oscillate. Problem (1) generalizes the ones recently studied in [6, 11].

The paper is organized as follows. In Section 2 we collect the necessary definitions and results of the nabla calculus on time scales, which are necessary in the sequel. In Section 3 we state and prove the new results: we prove necessary optimality conditions to problem (1), obtaining Euler–Lagrange type equations in the class of functions \( x \in C^1_{\text{ld}}(\mathbb{T}, \mathbb{R}^n) \) and new transversality conditions (Theorems 3.4 and 3.5).

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Part of first author’s Ph.D., which is carried out at the University of Aveiro under the Doctoral Programme in Mathematics and Applications of Universities of Aveiro and Minho.
2. Preliminaries. In this section we introduce basic definitions and theorems that are needed in Section 3. For more on the time scale theory we refer the reader to [1, 2, 13]. A time scale $\mathbb{T}$ is an arbitrary nonempty closed subset of $\mathbb{R}$. All the intervals in this paper are time scale intervals with respect to a given time scale $\mathbb{T}$ (for example, by $[a, b]$ we mean $[a, b] \cap \mathbb{T}$).

Definition 2.1 (e.g., Section 2.1 of [13]). The forward jump operator $\sigma : \mathbb{T} \to \mathbb{T}$ is defined by $\sigma(t) := \inf \{s \in \mathbb{T} : s > t\}$ for $t \neq \sup \mathbb{T}$ and $\sigma(\sup \mathbb{T}) = \sup \mathbb{T}$ if $\sup \mathbb{T} < +\infty$. Similarly, the backward jump operator $\rho : \mathbb{T} \to \mathbb{T}$ is defined by $\rho(t) := \sup \{s \in \mathbb{T} : s < t\}$ for $t \neq \inf \mathbb{T}$ and $\rho(\inf \mathbb{T}) = \inf \mathbb{T}$ if $\inf \mathbb{T} > -\infty$.

Definition 2.2 (e.g., Section 2.1 of [13]). The backward graininess function $\nu : \mathbb{T} \to [0, \infty)$ is defined by $\nu(t) := t - \rho(t)$.

A point $t \in \mathbb{T}$ is called right-dense, right-scattered, left-dense or left-scattered if $\sigma(t) = t$, $\sigma(t) > t$, $\rho(t) = t$, $\rho(t) < t$, respectively. We say that $t$ is isolated if $\rho(t) < t < \sigma(t)$, that $t$ is dense if $\rho(t) = t = \sigma(t)$. If $\mathbb{T}$ has a right-scattered minimum $m$, then define $\mathbb{T}_r := \mathbb{T} - \{m\}$; otherwise, set $\mathbb{T}_r := \mathbb{T}$. To simplify the notation, let $f^\sigma(t) := f(\rho(t))$.

Definition 2.3 (e.g., Section 2.2 of [13]). We say that function $f : \mathbb{T} \to \mathbb{R}$ is nabla differentiable at $t \in \mathbb{T}_r$ if there is a number $f^\nabla(t)$ such that for all $\epsilon > 0$ there exists a neighborhood $U$ of $t$ such that

$$|f^\sigma(t) - f(s) - f^\nabla(t)(\rho(t) - s)| \leq \epsilon|\rho(t) - s|$$

for all $s \in U$.

We call $f^\nabla(t)$ the nabla derivative of $f$ at $t$. Moreover, $f$ is nabla differentiable on $\mathbb{T}_r$ provided $f^\nabla(t)$ exists for all $t \in \mathbb{T}_r$.

Theorem 2.4 (e.g., Theorem 8.41 of [1]). Assume $f, g : \mathbb{T} \to \mathbb{R}$ are nabla differentiable at $t \in \mathbb{T}_r$. Then:

1. The sum $f + g : \mathbb{T} \to \mathbb{R}$ is nabla differentiable at $t$ with $(f + g)^\nabla(t) = f^\nabla(t) + g^\nabla(t)$.

2. For any constant $\alpha$, $\alpha f : \mathbb{T} \to \mathbb{R}$ is nabla differentiable at $t$ and $(\alpha f)^\nabla(t) = \alpha f^\nabla(t)$.

3. The product $fg : \mathbb{T} \to \mathbb{R}$ is nabla differentiable at $t$ and the following product rules hold:

$$(fg)^\nabla(t) = f^\nabla(t)g(t) + f^\sigma g^\nabla(t) = f^\nabla(t)g^\sigma(t) + f(t)g^\nabla(t).$$

4. If $g(t)g^\sigma(t) \neq 0$, then $f/g$ is nabla differentiable at $t$ and the following quotient rule hold:

$$(f/g)^\nabla(t) = \frac{f(t)g^\sigma(t) - f^\sigma(t)g(t)}{g(t)g^\sigma(t)}.$$

Definition 2.5 (e.g., Section 3.1 of [2]). Let $\mathbb{T}$ be a time scale, $f : \mathbb{T} \to \mathbb{R}$. We say that function $f$ is ld-continuous if it is continuous at left-dense points and its right-sided limits exist (finite) at all right-dense points.

Definition 2.6 (e.g., Definition 9 of [13]). A function $F : \mathbb{T} \to \mathbb{R}$ is called a nabla antiderivative of $f : \mathbb{T} \to \mathbb{R}$ provided $F^\nabla(t) = f(t)$ for all $t \in \mathbb{T}_r$. In this case we define the nabla integral of $f$ from $a$ to $b$ $(a, b \in \mathbb{T})$ by

$$\int_a^b f(t)^\nabla t := F(b) - F(a).$$
The set of all ld-continuous functions $f : T \to \mathbb{R}$ is denoted by $C_{ld} = C_{ld}(T, \mathbb{R})$, and the set of all nabla differentiable functions with ld-continuous derivative by $C_{1ld} = C_{1ld}(T, \mathbb{R})$.

**Theorem 2.7** (e.g., Theorem 8.45 of [1] or Theorem 11 of [13]). Every ld-continuous function $f$ has a nabla antiderivative $F$. In particular, if $a \in T$, then $F$ defined by
\[ F(t) = \int_a^t f(\tau) \nabla \tau, \quad t \in T, \]
is a nabla antiderivative of $f$.

**Theorem 2.8** (e.g., Theorem 8.47 of [1] or Theorem 12 of [13]). If $a, b \in T$, $a \leq b$, and $f, g \in C_{ld}(T, \mathbb{R})$, then
\begin{enumerate}
  \item $\int_a^b (f(t) + g(t)) \nabla t = \int_a^b f(t) \nabla t + \int_a^b g(t) \nabla t$;
  \item $\int_a^b f(t) \nabla t = 0$;
  \item $\int_a^b f(t) g(\tau) \nabla \tau = \int_a^b f(t) g(t)_{\tau=a}^b - \int_a^b f(\tau) g^\sigma(t) \nabla t$;
  \item If $f(t) > 0$ for all $a < t \leq b$, then $\int_a^b f(t) \nabla t > 0$;
  \item If $t \in T$, then $\int_t^{+\infty} f(\tau) \nabla \tau = \nu(t) f(t)$.
\end{enumerate}

**Definition 2.9.** If $a \in T$, $\sup T = +\infty$ and $f \in C_{ld}([a, +\infty[, \mathbb{R})$, then we define the improper nabla integral by
\[ \int_a^{+\infty} f(t) \nabla t := \lim_{b \to +\infty} \int_a^b f(t) \nabla t, \]
provided this limit exists (in $\mathbb{R} := \mathbb{R} \cup \{-\infty, +\infty\}$).

**Theorem 2.10** (e.g., [4]). Let $S$ and $T$ be subsets of a normed vector space. Let $f$ be a map defined on $T \times S$, having values in some complete normed vector space. Let $v$ be adherent to $S$ and $w$ adherent to $T$. Assume that
\begin{enumerate}
  \item $\lim_{x \to v} f(t, x)$ exists for each $t \in T$;
  \item $\lim_{t \to w} f(t, x)$ exists uniformly for $x \in S$.
\end{enumerate}
Then, $\lim_{(t, x) \to (w, v)} \lim_{x \to v} f(t, x)$, $\lim_{x \to v} \lim_{t \to w} f(t, x)$ and $\lim_{(t, x) \to (w, v)} f(t, x)$ all exist and are equal.

The next result can be easily obtained from Theorem 4 of [11] by using the delta-nabla duality theory of time scales [3, 9, 10].

**Theorem 2.11.** Suppose that $x_*$ is a local minimizer or local maximizer to problem
\[ \mathcal{L}(x) = \int_a^b L \left(t, x^\sigma(t), x^\nabla(t), z(t)\right) \nabla t \longrightarrow \text{extr}, \]
where the variable $z$ is the integral defined by

$$z(t) = \int_{a}^{t} g\left(\tau, x^{\rho}(\tau), x^{\nabla}(\tau)\right) \nabla \tau,$$

in the class of functions $x \in C_{1d}^{1}(T, \mathbb{R}^{n})$ satisfying the boundary conditions $x(a) = \alpha$ and $x(b) = \beta$. Then, $x_{*}$ satisfies the Euler–Lagrange system of equations

$$g_{x}(x)(t) \int_{\rho(t)}^{b} L_{z}[x, z](\tau) \nabla \tau - \left(g_{v}(x)(t) \int_{\rho(t)}^{b} L_{z}[x, z](\tau) \nabla \tau\right) \nabla + L_{x}[x, z](t) - L_{v}^{\nabla}[x, z](t) = 0$$

for all $t \in [a, b]$, where $L_{x}$, $L_{v}$ and $L_{z}$ are, respectively, the partial derivatives of $L(\cdot, \cdot, \cdot)$ with respect to its second, third and fourth argument, $g_{x}$ and $g_{v}$ are, respectively, the partial derivatives of $g(\cdot, \cdot, \cdot)$ with respect to its second and third argument, and the operators $[\cdot, \cdot]$ and $\langle \cdot \rangle$ are defined by $[x, z](t) := (t, x^{\rho}(t), x^{\nabla}(t), z(t))$ and $\langle x \rangle(t) := (t, x^{\rho}(t), x^{\nabla}(t))$.

3. Main Results. Let $T$ be a time scale such that $\text{sup} \; T = +\infty$. Suppose that $a, T, T' \in T$ are such that $T > a$ and $T' > a$. The meaning of $L(x, z)(t)$, $g(x)(t)$ and that of partial derivatives $L_{x}[x, z](t)$, $L_{v}[x, z](t)$ and $g_{x}(x)(t)$ is given in Theorem 2.11. Let us consider the following variational problem on $T$:

$$J(x) := \int_{a}^{\infty} L(x, z)(t) \nabla t = \int_{a}^{\infty} L(t, x^{\rho}(t), x^{\nabla}(t), z(t)) \nabla t \rightarrow \max$$

subject to $x(a) = x_{a}$. The variable $z$ is the integral defined by

$$z(t) := \int_{a}^{t} g(x)(\tau) \nabla \tau = \int_{a}^{t} g(\tau, x^{\rho}(\tau), x^{\nabla}(\tau)) \nabla \tau.$$

We assume that $x_{a} \in \mathbb{R}^{n}$, $n \in \mathbb{N}$, $(u, v, w) \rightarrow L(t, u, v, w)$ is a $C_{1d}^{1}(\mathbb{R}^{2n+1}, \mathbb{R})$ and $(u, v) \rightarrow g(t, u, v)$ a $C_{1d}^{1}(\mathbb{R}^{2n}, \mathbb{R})$ function for any $t \in T$, and functions $t \rightarrow L_{v}[x, z](t)$ and $t \rightarrow g_{v}(x)(t)$ are nabla differentiable for all $x \in C_{1d}^{1}(T, \mathbb{R}^{n})$.

**Definition 3.1.** We say that $x$ is an admissible path for problem (2) if $x \in C_{1d}^{1}(\mathbb{T}, \mathbb{R}^{n})$ and $x(a) = x_{a}$.

**Definition 3.2.** We say that $x_{*}$ is a weak maximizer to problem (2) if $x_{*}$ is an admissible path and, moreover,

$$\lim_{T \rightarrow +\infty} \inf_{T' \geq T} \int_{a}^{T'} (L[x, z](t) - L[x_{*}, z_{*}](t)) \nabla t \leq 0$$

for all admissible path $x$.

**Lemma 3.3.** Let $g \in C_{1d}(T, \mathbb{R})$. Then,

$$\lim_{T \rightarrow +\infty} \inf_{T' \geq T} \int_{a}^{T'} g(t) \eta^{\rho}(t) \nabla t = 0$$

for all $\eta \in C_{1d}(\mathbb{T}, \mathbb{R})$ such that $\eta(a) = 0$ if, and only if, $g(t) = 0$ on $[a, +\infty[$.
\begin{proof}
The implication $\Leftarrow$ is obvious. Let us prove the implication $\Rightarrow$ by contradiction. Suppose that $g(t) \not\equiv 0$. Let $t_0$ be a point on $[a, +\infty]$ such that $g(t_0) \neq 0$. Suppose, without loss of generality, that $g(t_0) > 0$. Two situations may occur: $t_0$ is left-dense (case I) or $t_0$ is left-scattered (case II). Case I: if $t_0$ is left-dense, then function $g$ is positive on $[t_1, t_0]$ for $t_1 < t_0$. Define:

$$\eta(t) = \begin{cases} (t_0 - t)(t - t_1) & \text{for } t \in [t_1, t_0], \\ 0 & \text{otherwise.} \end{cases}$$

Then,

$$\eta(\rho(t)) = \begin{cases} (t_0 - \rho(t)) (\rho(t) - t_1) & \text{for } \rho(t) \in [t_1, t_0], \\ 0 & \text{otherwise.} \end{cases}$$

If $\rho(t) \in [t_1, t_0]$, then $\eta(\rho(t)) = (t_0 - \rho(t))(\rho(t) - t_1) > 0$. Thus,

$$\lim_{T \to +\infty} \inf_{T' \geq T} \int_a^{T'} g(t) \eta'(t) \nabla t = \int_{t_1}^{t_0} g(t) \eta(\rho(t)) \nabla t > 0$$

and we obtain a contradiction. Case II: $t_0$ is left-scattered. Two situations are then possible: $\rho(t_0)$ is left-scattered or $\rho(t_0)$ is left-dense. If $\rho(t_0)$ is left-scattered, then $\rho(\rho(t_0)) < \rho(t_0) < t_0$. Let $t \in [\rho(t_0), t_0]$. Define

$$\eta(t) = \begin{cases} g(t_0) & \text{for } t = \rho(t_0), \\ 0 & \text{otherwise.} \end{cases}$$

Then,

$$\eta(\rho(t_0)) = \begin{cases} g(t_0) & \text{for } \rho(t_0) = \rho(\rho(t_0)), \\ 0 & \text{otherwise.} \end{cases}$$

It means that $\eta(\rho(t_0)) = g(t_0) > 0$. From point 5 of Theorem 2.8, we obtain

$$\lim_{T \to +\infty} \inf_{T' \geq T} \int_a^{T'} g(t) \eta'(t) \nabla t = \int_{\rho(t_0)}^{t_0} g(t) \eta(\rho(t)) \nabla t$$

$$= g(t_0) \eta(\rho(t_0)) \nu(t_0) = g(t_0)g(t_0)(t_0 - \rho(t_0)) > 0,$$

which is a contradiction. It remains to consider the situation when $\rho(t_0)$ is left-dense. Two cases are then possible: $g(\rho(t_0)) \neq 0$ or $g(\rho(t_0)) = 0$. If $g(\rho(t_0)) \neq 0$, then we can assume that $g(\rho(t_0)) > 0$ and $g$ is also positive in $[t_2, \rho(t_0)]$ for $t_2 < \rho(t_0)$. Define

$$\eta(t) = \begin{cases} (\rho(t_0) - t)(t - t_2) & \text{for } t \in [t_2, \rho(t_0)], \\ 0 & \text{otherwise.} \end{cases}$$

Then,

$$\eta(\rho(t)) = \begin{cases} (\rho(t_0) - \rho(t))(\rho(t) - t_2) & \text{for } \rho(t) \in [t_2, \rho(t_0)], \\ 0 & \text{otherwise.} \end{cases}$$

On the interval $[t_2, \rho(t_0)]$ the function $\eta(\rho(t))$ is greater than 0. Then,

$$\lim_{T \to +\infty} \inf_{T' \geq T} \int_a^{T'} g(t) \eta'(t) \nabla t = \int_{t_2}^{\rho(t_0)} g(t) \eta(\rho(t)) \nabla t > 0,$$

which is a contradiction. Suppose that $g(\rho(t_0)) = 0$. Here two situations may occur: (i) $g(t) = 0$ on $[t_3, \rho(t_0)]$ for some $t_3 < \rho(t_0)$ or (ii) for all $t_3 < \rho(t_0)$ there exists
that $t \in [t_3, \rho(t_0)]$ such that $g(t) \neq 0$. In case (i) $t_3 < \rho(t_0) < t_0$. Let us define

$$
\eta(t) = \begin{cases} 
g(t_0) & \text{for } t = \rho(t_0), 
\varphi(t) & \text{for } t \in [t_3, \rho(t_0)], 
0 & \text{otherwise},
\end{cases}
$$

for function $\varphi$ such that $\varphi \in C_{ld}$, $\varphi(t_3) = 0$ and $\varphi(\rho(t_0)) = g(t_0)$. Then,

$$
\eta(\rho(t)) = \begin{cases} 
g(t_0) & \text{for } \rho(t) = \rho(t_0), 
\varphi(\rho(t)) & \text{for } \rho(t) \in [t_3, \rho(t_0)], 
0 & \text{otherwise}.
\end{cases}
$$

It follows from point 5 of Theorem 2.8 that

$$
\lim_{T \to +\infty} \inf_{T' \geq T} \int_a^{T'} g(t)\eta^p(t)\nabla t = \int_{t_3}^{t_0} g(t)\eta^p(t)\nabla t = \int_{\rho(t_0)}^{t_0} g(t)\eta^p(t)\nabla t = \nu(t_0)g(t_0)\eta(\rho(t_0)) = (t_0 - \rho(t_0))g(t_0)\eta(\rho(t_0)) > 0,
$$

which is a contradiction. In case (ii), $t_3 < \rho(t_0) < t_0$. When $\rho(t_0)$ is left-dense, then there exists a strictly increasing sequence $S = \{s_k : k \in \mathbb{N}\} \subseteq \mathbb{T}$ such that $\lim_{k \to \infty} s_k = \rho(t_0)$ and $g(s_k) \neq 0$ for all $k \in \mathbb{N}$. If there exists a left-dense $s_k$, then we have Case I with $t_0 := s_k$. If all points of the sequence $S$ are left-scattered, then we have Case II with $t_0 := s_i$, $i \in \mathbb{N}$. Since $\rho(t_0)$ is a left-scattered point, we are in the first situation of case II and we obtain a contradiction. Therefore, we conclude that $g \equiv 0$ on $[a, +\infty[$.

**Corollary 1.** Let $h \in C_{ld}(\mathbb{T}, \mathbb{R})$. Then,

$$
\lim_{T \to +\infty} \inf_{T' \geq T} \int_a^{T'} h(t)\eta^\nabla(t)\nabla t = 0 \quad (3)
$$

for all $\eta \in C_{ld}(\mathbb{T}, \mathbb{R})$ such that $\eta(a) = 0$ if, and only if, $h(t) = c$, $c \in \mathbb{R}$, on $[a, +\infty[$.

**Proof.** Using integration by parts (third item of Theorem 2.8),

$$
\int_a^{T'} h(t)\eta^\nabla(t)\nabla t = h(t)\eta(t)|_{t=a}^{t=T'} - \int_a^{T'} h^\nabla(t)\eta^p(t)\nabla t = h(T')\eta(T') - \int_a^{T'} h^\nabla(t)\eta^p(t)\nabla t
$$

holds for all $\eta \in C_{ld}(\mathbb{T}, \mathbb{R})$. In particular, it holds for the subclass of $\eta$ with $\eta(T') = 0$ and (3) is equivalent to

$$
\lim_{T \to +\infty} \inf_{T' \geq T} \int_a^{T'} h^\nabla(t)\eta^p(t)\nabla t = 0.
$$

Using Lemma 3.3, we obtain $h^\nabla(t) = 0$, i.e., $h(t) = c$, $c \in \mathbb{R}$, on $[a, +\infty[$.

**Theorem 3.4.** Suppose that a weak maximizer to problem (2) exists and is given by $x_*$. Let $p \in C^1_{ld}(\mathbb{T}, \mathbb{R}^r)$ be such that $p(a) = 0$. Define

$$
A(\varepsilon, T') := \int_a^{T'} \frac{L(t, x_*^p(t) + \varepsilon p^p(t), x_*^\nabla(t) + \varepsilon p^\nabla(t), z_*(t, p)) - L[x_*, z_*](t)}{\varepsilon} \nabla t,
$$

where
Suppose that
\[ z_*(t,p) = \int_a^t g(x_*(\tau))d\tau, \]
where
\[ V_0 = V(V_0) \]
and
\[ V_0 = V(V_0) \]

Then,
\[ \lim_{T' \to \infty} V(\varepsilon, T') = \inf_{T' \geq T} V(\varepsilon, T'), \]
\[ V(\varepsilon) := \lim_{T \to \infty} V(\varepsilon, T). \]

Suppose that
1. \( \lim_{\varepsilon \to 0} \frac{V(\varepsilon, T)}{\varepsilon} \) exists for all \( T \);
2. \( \lim_{T \to \infty} \frac{V(\varepsilon, T)}{\varepsilon} \) exists uniformly for \( \varepsilon \);
3. for every \( T' > a, T > a, \varepsilon \in \mathbb{R} \setminus \{0\} \), there exists a sequence \( A(\varepsilon, T'_n) \) such that \( \lim_{n \to \infty} A(\varepsilon, T'_n) = \inf_{T' \geq T} A(\varepsilon, T') \) uniformly for \( \varepsilon \).

Then, \( x_* \) satisfies the Euler–Lagrange system of \( n \) equations
\[ \lim_{T \to \infty} \inf_{T' \geq T} \left\{ g_x(x)(t) \int L_{\varepsilon}(x, z)(\tau) d\tau - \left[ g_v(x)(t) \int L_{\varepsilon}(x, z)(\tau) d\tau \right] \right\} + L_{\varepsilon}(x, z)(t) - L_{\varepsilon}(x, z)(t) = 0 \quad (4) \]
for all \( t \in [a, +\infty[ \) and the transversality condition
\[ \lim_{T \to \infty} \inf_{T' \geq T} \{ x(T') : [L_{\varepsilon}(x, z)(T') + g_v(x)(T')\nu(T')L_{\varepsilon}(x, z)(T')] \} = 0. \quad (5) \]

Proof. If \( x_* \) is optimal, in the sense of Definition 3.2, then \( V(\varepsilon) \leq 0 \) for any \( \varepsilon \in \mathbb{R} \). Because \( V(0) = 0 \), then 0 is a maximizer of \( V \). We prove that \( V \) is differentiable at 0, thus \( V'(0) = 0 \). Note that
\[ 0 = V'(0) = \lim_{\varepsilon \to 0} \frac{V(\varepsilon)}{\varepsilon} = \lim_{\varepsilon \to 0} \frac{V(\varepsilon, T)}{\varepsilon} = \lim_{T \to \infty} \lim_{\varepsilon \to 0} \frac{V(\varepsilon, T)}{\varepsilon} = \lim_{T \to \infty} \inf_{T' \geq T} A(\varepsilon, T') = \lim_{T \to \infty} \lim_{\varepsilon \to 0} A(\varepsilon, T'_n) \]
\[ = \lim_{T \to \infty} \lim_{n \to \infty} \inf_{\varepsilon \to 0} A(\varepsilon, T'_n) = \lim_{T \to \infty} \inf_{T' \geq T} A(\varepsilon, T') \]
\[ = \lim_{T \to \infty} \inf_{T' \geq T} \lim_{\varepsilon \to 0} \int_a^{T'} \frac{L(t, x_*(t) + \varepsilon p(t), x_*(t) + \varepsilon p(t), z_*(t, p)) - L(x_*, z_*)}{\varepsilon} dt \]
\[ = \lim_{T \to \infty} \inf_{T' \geq T} \lim_{\varepsilon \to 0} \int_a^{T'} \frac{L(t, x_*(t) + \varepsilon p(t), x_*(t) + \varepsilon p(t), z_*(t, p)) - L(x_*, z_*)}{\varepsilon} dt, \]
that is,

$$\lim_{T \to \infty} \inf_{T' \geq T} \int_a^{T'} \left[ L_z[x_*, z_*](t) \cdot p^\rho(t) + L_v[x_*, z_*](t) \cdot p^\nabla(t) + L_z[x_*, z_*](t) \int_a^t (g_x(x_*) \cdot p^\rho(\tau) + g_v(x_*) \cdot p^\nabla(\tau)) \, d\tau \right] \, dt = 0. \tag{6}$$

Using the integration by parts formula given by point 3 of Theorem 2.8, we obtain:

$$\int_a^{T'} L_v[x_*, z_*](t) \cdot p^\nabla(t) \, dt = L_v[x_*, z_*](t) \cdot p(t)|_{t=a}^{t=T'} - \int_a^{T'} L_v^\nabla[x_*, z_*](t) \cdot p^\rho(t) \, dt$$

$$= L_v[x_*, z_*](T') \cdot p(T') - \int_a^{T'} L_v^\nabla[x_*, z_*](t) \cdot p^\rho(t) \, dt.$$

Next, we consider the last part of equation (6). First we use the third nabla differentiation formula of Theorem 2.4:

$$\left[ \int_a^{T'} L_z[x_*, z_*](\tau) \, d\tau \int_a^t (g_x(x_*) \cdot p^\rho(\tau) + g_v(x_*) \cdot p^\nabla(\tau)) \, d\tau \right] \, dt$$

$$= \left( \int_a^{T'} L_z[x_*, z_*](\tau) \, d\tau \right) \left( \int_a^t (g_x(x_*) \cdot p^\rho(\tau) + g_v(x_*) \cdot p^\nabla(\tau)) \, d\tau \right)$$

$$+ \left( \int_a^{T'} L_z[x_*, z_*](\tau) \, d\tau \right) \left( \left( \int_a^t (g_x(x_*) \cdot p^\rho(\tau) + g_v(x_*) \cdot p^\nabla(\tau)) \, d\tau \right) \right) \, dt$$

$$= -L_z[x_*, z_*](t) \int_a^t (g_x(x_*) \cdot p^\rho(\tau) + g_v(x_*) \cdot p^\nabla(\tau)) \, d\tau$$

$$+ \left( \int_a^{T'} L_z[x_*, z_*](\tau) \, d\tau \right) \left( g_x(x_*) \cdot p^\rho(t) + g_v(x_*) \cdot p^\nabla(t) \right).$$

Integrating both sides from $t = a$ to $t = T'$,

$$\int_a^{T'} \left[ \int_a^{T'} L_z[x_*, z_*](\tau) \, d\tau \int_a^t (g_x(x_*) \cdot p^\rho(\tau) + g_v(x_*) \cdot p^\nabla(\tau)) \, d\tau \right] \, dt$$

$$= -\int_a^{T'} \left[ L_z[x_*, z_*](t) \int_a^t (g_x(x_*) \cdot p^\rho(\tau) + g_v(x_*) \cdot p^\nabla(\tau)) \, d\tau \right] \, dt$$

$$+ \int_a^{T'} \left[ \int_a^{T'} L_z[x_*, z_*](\tau) \, d\tau \left( g_x(x_*) \cdot p^\rho(t) + g_v(x_*) \cdot p^\nabla(t) \right) \right] \, dt.$$
The left-hand side of above equation is zero,
\[
\int_{a}^{T'} \int_{a}^{t} L_{z} [x_{*}, z_{*}] (\tau) \nabla t \left( g_{x} (x_{*}) (\tau) \cdot p^0 (\tau) + g_{v} (x_{*}) (\tau) \cdot p \nabla (\tau) \right) \nabla t \\
= \int_{a}^{T'} \int_{a}^{t} L_{z} [x_{*}, z_{*}] (\tau) \nabla t \left( g_{x} (x_{*}) (\tau) \cdot p^0 (\tau) + g_{v} (x_{*}) (\tau) \cdot p \nabla (\tau) \right) \nabla t \bigg|_{t=a}^{t=T'} = 0,
\]
and, therefore,
\[
\int_{a}^{T'} \left[ L_{z} [x_{*}, z_{*}] (t) \int_{a}^{t} g_{x} (x_{*}) (\tau) \cdot p^0 (\tau) + g_{v} (x_{*}) (\tau) \cdot p \nabla (\tau) \right] \nabla t \\
= \int_{a}^{T'} \left[ \int_{a}^{T'} L_{z} [x_{*}, z_{*}] (\tau) \nabla t \left( g_{x} (x_{*}) (t) \cdot p^0 (t) + g_{v} (x_{*}) (t) \cdot p \nabla (t) \right) \right] \nabla t \\
= \int_{a}^{T'} \left[ g_{x} (x_{*}) (t) \cdot p^0 (t) \int_{a}^{T'} L_{z} [x_{*}, z_{*}] (\tau) \nabla t \right] \nabla t \\
+ \int_{a}^{T'} \left[ p \nabla (t) \cdot g_{v} (x_{*}) (t) \int_{a}^{T'} L_{z} [x_{*}, z_{*}] (\tau) \nabla t \right] \nabla t.
\]
Using point 3 of Theorem 2.8 and the fact that \( p(a) = 0 \),
\[
\int_{a}^{T'} \left[ p \nabla (t) \cdot g_{v} (x_{*}) (t) \int_{a}^{T'} L_{z} [x_{*}, z_{*}] (\tau) \nabla t \right] \nabla t \\
= p(T') \cdot g_{v} (x_{*}) (T') \int_{a}^{T'} L_{z} [x_{*}, z_{*}] (\tau) \nabla t \\
- \int_{a}^{T'} \left( g_{v} (x_{*}) (t) \int_{a}^{T'} L_{z} [x_{*}, z_{*}] (\tau) \nabla t \right) \cdot p^0 (t) \nabla t.
\]
Then, from (6),
\[
\lim_{T \to \infty} \inf_{T' \geq T} \int_{a}^{T'} L_{z} [x_{*}, z_{*}] (t) \cdot p^0 (t) \nabla t + L_{v} [x_{*}, z_{*}] (T') \cdot p (T') - \int_{a}^{T'} L_{z} [x_{*}, z_{*}] (t) \cdot p^0 (t) \nabla t \\
+ \int_{a}^{T'} \left( \int_{a}^{T'} L_{z} [x_{*}, z_{*}] (\tau) \nabla t \left( g_{x} (x_{*}) (t) \cdot p^0 (t) + g_{v} (x_{*}) (t) \cdot p \nabla (t) \right) \right) \nabla t
\]
\[
\begin{aligned}
\lim_{T \to \infty} \inf_{T' \geq T} & \int_a^{T'} \left\{ T^t \frac{d}{dt} \right[ L_x[x_*, z_*](t) \cdot p^\rho(t) + L_v[x_*, z_*](T') \cdot p(T') \\
& - \int_a^{T'} \left\{ L_v^\rho(x_*, z_*)(t) \cdot p^\rho(t) + \int_{\rho(t)}^{T'} L_z[x_*, z_*](\tau) \nabla \tau g_x(x_*)(t) \cdot p^\rho(t) \right\} \nabla t \\
& + \int_a^{T'} \frac{d}{dt} \left( g_v(x_*)(t) \int_{\rho(t)}^{T'} L_z[x_*, z_*](\tau) \nabla \tau \right) \cdot p^\rho(t) \nabla t \\
& - \int_a^{T'} \left( \frac{d}{dt} \left( g_v(x_*)(t) \int_{\rho(t)}^{T'} L_z[x_*, z_*](\tau) \nabla \tau \right) \right) \nabla t \\
& + L_v[x_*, z_*](T') \cdot p(T') + \left( g_v(x_*)(t) \int_{\rho(t)}^{T'} L_z[x_*, z_*](\tau) \nabla \tau \right) \cdot p(T') \right\} = 0. \\
\end{aligned}
\]

We know that equation (8) holds for all \( p \in C^1_{ld} \) such that \( p(a) = 0 \), then, in particular, it also holds for the subclass of \( p \) with \( p(T') = 0 \). Therefore,

\[
\lim_{T \to \infty} \inf_{T' \geq T} \int_a^{T'} \left( \frac{d}{dt} \right) \left[ L_x[x_*, z_*](t) - L_v^\rho[x_*, z_*](t) + g_x(x_*)(t) \int_{\rho(t)}^{T'} L_z[x_*, z_*](\tau) \nabla \tau \\
- \left( g_v(x_*)(t) \int_{\rho(t)}^{T'} L_z[x_*, z_*](\tau) \nabla \tau \right) \right] \nabla t = 0.
\]

Choosing \( p = (p_1, \ldots, p_n) \) such that \( p_2 \equiv \cdots \equiv p_n \equiv 0 \),

\[
\lim_{T \to \infty} \inf_{T' \geq T} \int_a^{T'} \left( \frac{d}{dt} \right) \left[ L_{x_1}[x_*, z_*](t) + g_{x_1}(x_*)(t) \int_{\rho(t)}^{T'} L_z[x_*, z_*](\tau) \nabla \tau \\
- \left( g_{v_1}(x_*)(t) \int_{\rho(t)}^{T'} L_z[x_*, z_*](\tau) \nabla \tau \right) \right] \nabla t = 0.
\]
Using Lemma 3.3,
\[
\begin{align*}
g_{x_1}(x_*) &\int_{\rho(t)}^{T'} \langle L_x[x_*, z_*](\tau) \rangle \nabla T - \left( g_{v_1}(x_*) \int_{\rho(t)}^{T'} \langle L_z[x_*, z_*](\tau) \rangle \nabla T \right) \\
&+ L_{x_1}[x_*, z_*](t) - L_{v_1}[x_*, z_*](t) = 0
\end{align*}
\]
for all \( t \in [a, +\infty] \) and all \( T' \geq t \). We can do the same for other coordinates. For all \( i = 1, \ldots, n \) we obtain the equation
\[
\begin{align*}
g_{x_i}(x_*) &\int_{\rho(t)}^{T'} \langle L_x[x_*, z_*](\tau) \rangle \nabla T - \left( g_{v_i}(x_*) \int_{\rho(t)}^{T'} \langle L_z[x_*, z_*](\tau) \rangle \nabla T \right) \\
&+ L_{x_i}[x_*, z_*](t) - L_{v_i}[x_*, z_*](t) = 0
\end{align*}
\]
for all \( t \in [a, +\infty] \) and all \( T' \geq t \). These \( n \) conditions can be written in vector form as
\[
\begin{align*}
g_{x}(x_*) &\int_{\rho(t)}^{T'} \langle L_x[x_*, z_*](\tau) \rangle \nabla T - \left( g_{v}(x_*) \int_{\rho(t)}^{T'} \langle L_z[x_*, z_*](\tau) \rangle \nabla T \right) \\
&+ L_{x}[x_*, z_*](t) - L_{v}[x_*, z_*](t) = 0
\end{align*}
\]
for all \( t \in [a, +\infty] \) and all \( T' \geq t \), which implies the Euler–Lagrange system of \( n \) equations (4). From the system of equations (9) and equation (8), we conclude that
\[
\lim_{T \to \infty} \inf_{T' \geq T} \left\{ \left( L_v[x_*, z_*](T') + g_v(x_*)(T') \int_{\rho(T')}^{T'} \langle L_z[x_*, z_*](\tau) \rangle \nabla T \right) \cdot p(T') \right\} = 0.
\]
(10)

Next, we define a special curve \( p \): for all \( t \in [a, \infty[ \)
\[
p(t) = \alpha(t)x_*(t),
\]
(11)
where \( \alpha : [a, \infty[ \to \mathbb{R} \) is a \( C^1 \) function satisfying \( \alpha(a) = 0 \) and for which there exists \( T_0 \in T \) such that \( \alpha(t) = \beta \in \mathbb{R} \setminus \{0\} \) for all \( t > T_0 \). Substituting \( p(T') = \alpha(T')x_*(T') \) into (10), we conclude that
\[
\lim_{T \to \infty} \inf_{T' \geq T} \left\{ L_v[x_*, z_*](T') \cdot \beta x_*(T') + g_v(x_*)(T') \int_{\rho(T')}^{T'} \langle L_z[x_*, z_*](\tau) \rangle \nabla T \cdot \beta x_*(T') \right\}
\]
vanishes and, therefore,
\[
\lim_{T \to \infty} \inf_{T' \geq T} \left\{ x_*(T') \cdot \left[ L_v[x_*, z_*](T') + g_v(x_*)(T') \int_{\rho(T')}^{T'} \langle L_z[x_*, z_*](\tau) \rangle \nabla T \right] \right\} = 0.
\]
From item 5 of Theorem 2.8, \( x_* \) satisfies the transversality condition (5). \( \square \)
In contrast with Theorem 3.4, the following theorem is proved by manipulating equation (6) differently: using integration by parts and nabla differentiation formulas, we transform the items which consist of \( p' \) into \( p' \). Thanks to that, we apply Corollary 1 instead of Lemma 3.3 to obtain the intended conclusions.

**Theorem 3.5.** Under assumptions of Theorem 3.4, the Euler–Lagrange system of \( n \) equations

\[
\lim_{T \to \infty} \inf_{T' \geq T} \left\{ \int_T^{T'} g_x(x_*)(\tau) \int_T^{T'} L_z[x_*, z_*(\tau)] \nabla s \nabla \tau + g_v(x_*)(t) \int_T^{T'} L_z[x_*, z_*(\tau)] \nabla \tau \right\}
\]

\[
+ L_v[x_*, z_*(t)] - \int_a^t L_z[x_*, z_*(\tau)] \nabla \tau = c \quad (12)
\]

holds for all \( t \in [a, \infty[, c \in \mathbb{R}^n \), together with the transversality condition

\[
\lim_{T \to \infty} \inf_{T' \geq T} \left\{ x_*(T') \cdot \int_a^{T'} L_z[x_*, z_*(\tau)] \nabla \tau \right\} = 0. \quad (13)
\]

Proof. We use the necessary optimality condition (6) found in the proof of Theorem 3.4. Using point 3 of Theorem 2.4,

\[
\left[ p(t) \cdot \int_a^t L_z[x_*, z_*(\tau)] \nabla \tau \right] \nabla t
\]

\[
= p' \left( t \cdot \int_a^t L_z[x_*, z_*(\tau)] \nabla \tau \right) + p(t) \cdot \left[ \int_a^t L_z[x_*, z_*(\tau)] \nabla \tau \right] \nabla t
\]

\[
= p' \left( t \cdot \int_a^t L_z[x_*, z_*(\tau)] \nabla \tau \right) + p(t) \cdot L_z[x_*, z_*(\tau)] \nabla t.
\]

Then, integrating both sides from \( t = a \) to \( t = T' \),

\[
\int_a^{T'} \left[ p(t) \cdot \int_a^t L_z[x_*, z_*(\tau)] \nabla \tau \right] \nabla t
\]

\[
= \int_a^{T'} \left( p' \left( t \cdot \int_a^t L_z[x_*, z_*(\tau)] \nabla \tau \right) \right) \nabla t + \int_a^{T'} p(t) \cdot L_z[x_*, z_*(\tau)] \nabla t.
\]

Therefore,

\[
p(t) \cdot \int_a^t L_z[x_*, z_*(\tau)] \nabla \tau \bigg|_{t=T'}
\]

\[
= \int_a^{T'} \left( p' \left( t \cdot \int_a^t L_z[x_*, z_*(\tau)] \nabla \tau \right) \right) \nabla t + \int_a^{T'} p(t) \cdot L_z[x_*, z_*(\tau)] \nabla t.
\]
Since \( p(a) = 0 \), we obtain that \( p(T') \cdot \int_a^{T'} L_z[x_*, z_*](\tau) \nabla \tau \) is equal to

\[
\int_a^{T'} p^\nabla (t) \cdot \left( \int_a^t L_z[x_*, z_*](\tau) \nabla \tau \right) \nabla t + \int_a^{T'} p^\rho (t) \cdot L_z[x_*, z_*](t) \nabla t,
\]

that is,

\[
\int_a^{T'} p^\rho (t) \cdot L_z[x_*, z_*](t) \nabla t = - \int_a^{T'} p^\nabla (t) \cdot \left( \int_a^t L_z[x_*, z_*](\tau) \nabla \tau \right) \nabla t + p(T') \cdot \int_a^{T'} L_z[x_*, z_*](\tau) \nabla \tau.
\]

Making the same calculations as in the proof of Theorem 3.4, we obtain (7). Using again point 3 of Theorem 2.4,

\[
\left[ p(t) \cdot \int_t^{T'} \left( g_x(x_*) \cdot \int_{\rho(\tau)}^{T'} L_z[x_*, z_*](s) \nabla s \right) \nabla \tau \right] \nabla \tau
\]

\[
= p^\nabla (t) \cdot \int_t^{T'} \left( g_x(x_*) \cdot \int_{\rho(\tau)}^{T'} L_z[x_*, z_*](s) \nabla s \right) \nabla \tau + p^\rho (t) \cdot \int_t^{T'} \left( g_x(x_*) \cdot \int_{\rho(\tau)}^{T'} L_z[x_*, z_*](s) \nabla s \right) \nabla \tau
\]

\[
= p^\nabla (t) \cdot \int_t^{T'} \left( g_x(x_*) \cdot \int_{\rho(\tau)}^{T'} L_z[x_*, z_*](s) \nabla s \right) \nabla \tau
\]

\[
- p^\rho (t) \cdot g_x(x_*) \cdot \int_{\rho(t)}^{T'} L_z[x_*, z_*](\tau) \nabla \tau.
\]

Integrating both sides from \( t = a \) to \( t = T' \), and because of point 2 of Theorem 2.8 and \( p(a) = 0 \),

\[
\int_a^{T'} \left[ p(t) \cdot \int_t^{T'} \left( g_x(x_*) \cdot \int_{\rho(\tau)}^{T'} L_z[x_*, z_*](s) \nabla s \right) \nabla \tau \right] \nabla \tau \nabla t
\]

\[
= p(t) \cdot \int_t^{T'} \left( g_x(x_*) \cdot \int_{\rho(\tau)}^{T'} L_z[x_*, z_*](s) \nabla s \right) \nabla \tau \nabla t \bigg|_{t=a}^{T'} = 0.
\]
Then,

\[
\int_a^{T'} p^\rho(t) \cdot \left( g_{x'}(x_s)(t) \int_{\rho(t)}^{T'} L_z[x_s, z_s](s) \nabla s \right) \nabla t
\]

\[
= \int_a^{T'} p^\nabla(t) \cdot \left[ \int_t^{T'} \left( g_{x'}(x_s)(\tau) \int_{\rho(\tau)}^{T'} L_z[x_s, z_s](s) \nabla s \right) \nabla \tau \right] \nabla t.
\]

From (7) and previous relations, we write (6) in the following way:

\[
\lim_{T \to \infty} \inf_{T' \geq T} \left\{ \int_a^{T'} p^\nabla(t) \cdot \left[ \int_a^{T'} \left( -L_z[x_s, z_s]\nabla_t + L_v[x_s, z_s](t) \right) \right] - \left( \int_a^{T'} L_v[x_s, z_s](t) \nabla_t \right) \nabla t \right\} = 0.
\]

(14)

Because (14) holds for all \( p \in C_{lid} \) with \( p(a) = 0 \), in particular it also holds in the subclass of functions \( p \in C_{lid} \) with \( p(a) = p(T') = 0 \). Let \( i \in \{1, \ldots, n\} \). Choosing \( p = (p_1, \ldots, p_n) \) such that all \( p_j = 0, j \neq i \), and \( p_i \in C_{lid} \) with \( p_i(a) = p_i(T') = 0 \), we conclude that

\[
\lim_{T \to \infty} \inf_{T' \geq T} \int_a^{T'} p_i^\nabla(t) \left\{ \int_a^{T'} \left( -L_{z_i}[x_s, z_s]\nabla_t + L_{v_i}[x_s, z_s](t) \right) \right\} \nabla t = 0.
\]
From Corollary 1 we obtain the equations

\[
L_{v_i}[x_\ast, z_\ast](t) - \int_\alpha^t L_{x_i}[x_\ast, z_\ast](\tau) \nabla \tau + \int_\alpha^{T'} \left( g_{x_i}(x_\ast)(\tau) \int_{\rho(\tau)}^{T'} L_{z}[x_\ast, z_\ast](s) \nabla s \right) \nabla \tau + g_{v_i}(x_\ast)(t) \int_{\rho(t)}^{T'} L_{z}[x_\ast, z_\ast](\tau) \nabla \tau = c_i, \tag{15}
\]

\(c_i \in \mathbb{R}, i = 1, \ldots, n\), for all \(t \in [\alpha, +\infty]\) and all \(T' \geq t\). These \(n\) conditions imply the Euler–Lagrange system of equations (12). From (14) and (15), we conclude that

\[
\lim_{T \to \infty} \inf_{T' \geq T} \left\{ p(T') \cdot \int_\alpha^{T'} L_{x}[x_\ast, z_\ast](\tau) \nabla \tau \right\} = 0. \tag{16}
\]

Using the special curve \(p\) defined by (11), we obtain from equation (16) that

\[
\lim_{T \to \infty} \inf_{T' \geq T} \left\{ \beta x_\ast(T') \cdot \int_\alpha^{T'} L_{z}[x_\ast, z_\ast](\tau) \nabla \tau \right\} = 0.
\]

Therefore, \(x_\ast\) satisfies the transversality condition (13). \(\square\)

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